

PH.D Thesis In Information Engineering

Bilateral Aerial Tele-Manipulation: Single and Multi-Robot Approaches

by

Mostafa Mohammadi

Department of Information Engineering And Mathematics



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Mostafa Mohammadi

Advisor: Prof. Domenico Prattichizzo

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Mostafa Mohammadi,

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Dedication

This is dedicated to my amazing friend and wife,
Zahra

Acknowledgments

I would like to express my tremendous gratitude to all the people who helped me to start, continue, and conclude my research work. It is impossible for me to name them all here.

I would like to present my great appreciation to Professor Domenico Prattichizzo, my advisor that allowed me to understand what I really like. The high degree of autonomy he granted me during my Ph.D. let me enjoy different fields of robotics science. I never had any limitation to access whatever I needed in research. I will never forget that I was always sure that his great expertise in the field of grasping and haptics will never let me stop in any stage of my work.

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How can I express my feeling for the years of my wife living alone to let me do this? Thanks a lot Zahra.

Abstract

This Thesis focuses on bilateral aerial tele-manipulation and studies the aerial manipulation with Multi-Rotor Aerial Robots (MRAR). Differently from other approaches that are considering an arm and a hand mounted on an aerial vehicle, we propose lightweight passive arms that are installed on the vehicle either rigidly or through multi-degrees of freedom joints. The manipulation capability for the arm is provided by the motion of the MRAR. Using this lightweight passive arms allows to utilize the power of small size MRARs more for manipulation purposes rather than tolerating the weight of the arm. The MRAR equipped with the lightweight passive arm can perform force tracking tasks simply, *i.e.*, can apply desired force vectors to the objects in environment. Then, more complex tasks are possible by utilizing a team of MRARs, in which each robot plays the role of a finger, making the flying hand dexterous to perform manipulation tasks. In order to cope with unknown, unstructured environment tele-operation approach is chosen. Moreover, to enhance the situational awareness of the user from remote side, bilateral teleoperation approach is used in which the human operator is provided with haptic feedback in the force form. This Thesis is organized to follow the same structure used in the described research: i) theory, ii) simulation, and iii) experiments.

The thesis starts with the problem of parallel position/force control in bilateral aerial tool operation. A quadrotor MRAR equipped with a lightweight passive tool, composed of a rigid link and a compliant joint at the end-effector, applying desired force vectors, is used. A bilateral teleoperation scheme is proposed to enable the human operator to drive a quadrotor using a unified controller in free flight and in contact interaction. In the first case, in order to cope with the usually limited workspace of the master-side teleoperation device, we map position to speed, thus overcoming any space-related limitation. The master device position during the contact interaction is instead interpreted as desired force to apply to the environment. The desired position and force are blended by a parallel

position/force controller in which the force is regulated by a PI-controller that augments the desired position commanded by the operator with corresponding additional position reference. Assuming a hard-finger contact model, the contact maintenance is considered by keeping the commanded force vector in the friction cone. The human operator is provided with force feedback depending on the position error in free flight and on the force error in contact.

The natural development of the aforementioned study is a bilateral tele-operation scheme for cooperative aerial manipulation in which a human operator drives a team of MRARs, which grasped an object beforehand, and receives a force feedback depending on the state of the system. The hardware consists of a rigid tool attached to the vehicle through a passive spherical joint equipped with a simple adhesive mechanism at the tool-tip that can stick to the grasped object. Having more than two robots, we use the extra DoFs to find the optimal force allocation in term of minimum power and forces smoothness. In such framework the human operator commands desired trajectory of the object for the robot team through a haptic interface. Then an object pose controller specifies the desired total wrench to be applied to the object by the MRAR team. The system constraints, *e.g.*, MRAR limited forces and contact maintenance, defines the feasible set of forces. Then, the output of the pose controller, along with system constraints, are mapped in the form of an optimization problem that allocates forces by minimizing a cost function comprising forces and their variation. Finally, propeller thrusts are computed by a dedicated attitude and thrust controller in a decentralized fashion.

The thesis is concluded presenting a heterogeneous multi-robot system of Multiple Aerial-Ground Manipulating Systems (MAGMaS). These systems associate grounded manipulators to aerial robots in order to benefit from the advantages of both kinds of platforms, *i.e.*, physical strength versus large workspace. The dynamic model of such a robotic system is derived, and its characteristic structure exhibited. Considering a set of tasks and taking advantage of the dynamical structure, a robust nonlinear control scheme with disturbance observer is derived allowing to achieve precise trajectory tracking in the presence of model uncertainties. The system redundancy is exploited by solving an optimal force/torque allocation problem that takes into account the real system constraints and maximizes the overall manipulability.

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Introduction

This chapter starts with a brief conceptual overview of the essential elements that are needed throughout the Thesis. Then, ideas, approaches, and the overall perspective of the Thesis are given.

1.1 Multi-Rotor Aerial Robots

Aerial vehicles can be categorized into manned and unmanned groups. In this Thesis small size Vertical-Take-Off-and-Landing (VTOL) Unmanned Aerial Vehicles (UAV) are utilized for aerial manipulation tasks. They don't need any open and smooth area, like airstrip, for take-off and landing, they also do not need overhead throw-off to get the initial velocity in order to overcome their weight. Their rotary wings, most of the time known as propellers, as opposed to flapping wings of bird-like robots, and fixed wings of airplanes, enables them do take-off and land vertically. But there is a trade-off between VTOL-capability and payload per power consumption ratio for these vehicles [1]. Depending on the application, VTOL-UAVs come in configurations with different number of rotors, such as traditional helicopter, ducted fan, and quadrotor. In the last decade, quadrotors have become the most common type in research due to their simple mechanical structure and high maneuverability [1].

The real growth of unmanned type of Multi-Rotor Aerial Vehicles has taken place in the last decade. This is due the recent technological advancements in electronics and electrical engineering, that made it possible to fabricate small yet very powerful motors, in particular Brush-Less DC motors (BLDC), and small batteries with high capacity, *e.g.*, Li-Po Batteries. Moreover, with the emerge of Micro-Electro-Mechanical-Systems (MEMS), development of small size on-board inertial sensors, namely accelerometer and gyroscope, have progressed significantly. Beside this, the accelerated growth of computer technology brings in the feasibility of small computers with high capabilities and reduced power consumption. All these technological progression promoted the research field of Multi-Rotor Aerial Robots (MRAR).

MRAR is an interesting robotic field with a wide range of applications. Aerial

photography has been the traditional first duty of all aerial robots. Aerial photography in variety of applications such as entertaining selfie image capturing, agriculture field inspection, construction site management, and border line patrolling. It is worth noting that small size VTOLs are not the best choice for high endurance missions such as border line inspection and patrolling, and indeed fixed-wing aircrafts are better suited for this purpose. Instead, when it comes to short range missions with short flight time, such as robotic search and rescue scenarios, or building inspection, or power line monitoring in order to fault diagnosis, MRARs are particularly adequate because of their vertical and landing capabilities and because of their high maneuverability and agility [2]. Load carrying is another important role of MRARs, that will form an important aspect of the future perspective of aerial robotics, as major distribution companies are working on delivery service using MRARs[3].

Only recently aerial manipulation has been introduced as another functionality of MRARs, where an aerial robot (or a team of aerial robots) is equipped with a tool such as robotic arm, parallel structure end-effector, gripper, passive arm, or a combination of them, to interact with its own environment. Aerial manipulation has opened a window to a new era of robotics where aerial robots go beyond the sensing oriented inspection applications, and even further than load transportation. In aerial manipulation aerial robots are sensing, reasoning/being teleoperated, moving, and acting on their environment.

Aerial manipulation with MRAR makes it possible to act after or at the same time of inspection. For example consider an aerial robot, such as a quadrotor UAV, which has been flown to see a tall structure such as a distillation column or a wind turbine; after inspection, once the fault is detected, a human should go there and fix it. Thanks to aerial manipulation, in many cases, there will be no need for a human to go there and fix the problem and the flying machine will resolve the problem. For another type of application, consider a hazardous area where human cannot access easily and safely due to pollution or height or temperature or other threatening conditions. Then after inspection by the aerial robot, without capability of manipulation the mission will be left incomplete or expose an operator to the hazardous area. In this cases manipulation is a necessity. Although there might be some other ways to manipulate the targeted object in a given environment, aerial manipulation seems really appealing and promising: 1) small size MRARs have a high capability in reaching inaccessible places for ground robots, such as a roof or a window located in a high altitude, 2) small size MRARs are faster than ground mobile-manipulator 3) in many cases small size MRARs are economically more affordable than ground mobile manipulators. To make it clearer, assume a place in fire, with an aerial robot equipped with a camera and a tool, as we shall see in the next chapter, one can send the robot inside the building to shut-down the main electricity switch or

close the main gas tap. It is hard even to imagine a mobile manipulator to accomplish this task, especially when the target point is not in the first floor and when the building have stairs. This and countless number of other examples brings to mind the use of aerial manipulation in robotic search and rescue where the human-robot teaming is of utmost importance in order to improve the success rate. Aerial manipulation, which is the heart of this Thesis, involves however significant challenges.

MRARs are intrinsically unstable, which means it is impossible to control them in an open-loop fashion. Most of the control approaches are exploiting the symmetrical geometry and mechanical balance of the system in designing the stabilizing controller. Moreover, in most of the cases the robot is controlled in free flight and the only external forces that are acting on the robot are smooth winds, and there is no serious external force on the vehicle, apart its weight. These conditions are violated in aerial manipulation: when an arm attached to the robot, its center of mass (CoM) is not the "center of the robot" anymore. When the robot with its tool is in contact with environment, e.g., holding an object or pushing a switch or pushing a cart, the situation deteriorates and demands new control approaches and mechanical considerations. Furthermore, most of the MRARs are mechanically under-actuated, *i.e.*, their longitudinal and latitudinal motion is controlled by orientation control. This make the force control of the robot much more difficult while physically interacting with the environment. In the past few years, there have been some attempts to carry out aerial manipulation by assembling arms and grippers on helicopters (Fig. 1.1). In order to solve the aforementioned problems, we utilized simple light-weight passive¹ arms with suitable mechanical considerations, and the interaction forces are regulated by controlling the robot motion. The arm is composed of a rod and an end-effector, that is attached to the robot from above or below either rigidly or using mechanical joints.

This helps to accomplish the aerial manipulation task in the following ways:

- ◇ a light weight passive arm will impose less load to the MRAR, thus MRAR's power is spent on applying higher force instead of carrying an actuated arm and powering its motors;
- ◇ with a light-weight passive arm the flight time increases, note that these kind of vehicles have a limited flight time, e.g., in our case is about 10 minutes;
- ◇ using light weight passive arms one can achieve a more agile flight during the free flight;

¹The term "passive" here is used to indicate that there is no actuating component, such as motors or linear actuators, on the arm.



Figure 1.1: Examples of works in aerial manipulation with conventional helicopters with actuated robotic arms. (a) Aerial manipulation robot composed of an autonomous helicopter and a 7 degrees of freedom industrial manipulator [4], (b) small scale UAV helicopters with added payload mass [5], (c) visual servoing for aerial manipulation using a 7 degrees of freedom industrial manipulator [6].

- ◇ in aerial manipulation with a single MRAR, the current hierarchical control algorithms for position and orientation control remain the same and only an extra outer loop to regulate the force is needed, and also in cooperative manipulation schemes the orientation control loop remains the same, thus common commercial MRARs can also be utilized for aerial manipulation by small modifications in their control algorithm;
- ◇ the proposed light-weight passive tools are very cost-effective in term of development and also maintenance.

Thus, for aerial manipulation scenarios where dexterous manipulation by each vehicle is not necessary, light-weight passive tools are preferable, while for more complicated tasks cooperative schemes by a team of robots can be a solution.

1.2 Bilateral Teleoperation

The next step is to realize how an MRAR performs its task. More in details, how the robot can perceive its own-environment to reach the target point, where the robot wants to grasp, push, pull, and in general apply force, without running into obstacles in the environment. The problem seems even more difficult when the destination is unknown, and the robot must search for it in a cluttered environment. There are several other problems that make

it extremely hard, if not impossible, to deploy MRARs in a real situation, autonomously. The level of intelligence and perception in robotics is still far from the stage that allow us to perform the aerial manipulation autonomously² [7]. Thus, a human in the loop can be a good solution. A human operator that can see the environment in which the robot perform the mission (*e.g.*, through on-board cameras on the robot), so can guide the robot in appropriate directions, and also can recognize goals and command the robot to reach them. Furthermore, with the current level of technology the human operator is also able to perceive the physical interaction of the robot. Following the idea of human in the loop, this Thesis utilizes teleoperation strategy to perform aerial manipulation with MRAR.

Teleoperation is a widely accepted and common approach to perform actions from afar. A robotic teleoperation system is composed of the following components: human operator, master robot(s) and its controller, slave robot(s) and its controller, remote environment, and a communication channel between the master and slave robots³. The idea of teleoperation is simple: the slave robot, *i.e.*, the robot in remote side, should replicate the action of the master robot, *i.e.*, the robot that the human operator is working with. On the other hand the concept of bilateral teleoperation have augmented the idea of teleoperation by giving the possibility of sensing the remote environment to the human operator through the master robot.

Depending on the application there are different bilateral teleoperation schemes. The command that the slave robot might be asked to perform can be either force or velocity⁴ and the interaction that the human operator can feel might be either force or velocity. The requirements of the task determines the teleoperation scheme.

If the slave robot is asked to perform a single type of command, *i.e.*, only force or only velocity, and human operator receives only a single type of feedback, *i.e.*, either force or velocity, this architecture is called 2-channel-bilateral-teleoperation. If the slave robot is asked to perform two kinds of commands at the same time, *i.e.*, both force and velocity, and in the master side human operator is provided only with a single type of feedback, this architecture is known as 3-channel-bilateral-teleoperation. And finally, if the master robot is asked to follow both force and velocity commands at the same time, human operator is also provided with both kind of feedbacks, then you have a 4-channel-bilateral-teleoperation [8, 9]. There is another important taxonomy for 2-

²And the purpose of the present Thesis is not to push the boundary of intelligence and perception in the aerial manipulation.

³Note that the remote side and the remote robot, can be either real or virtual, *i.e.*, simulated environment and robot in a computer software.

⁴In most of the cases position can be interchangeably used with velocity considering minor modifications in the scheme.

channel-bilateral-teleoperation in terms of action and reaction in the master and slave sides, this taxonomy is based on the following two definitions [10]:

Impedance device: receives a force command and applies force to its environment in response to its measured position.

Admittance device: receives a velocity/position command and applies a velocity/position to its environment in response to its measured contact force.

This typology applies to both master and slave robots. If the master robot is commanded in position/velocity, i.e., the human operator changes the position/velocity of the master robot by applying force to it, and at the same time the human operator is provided with force feedback proportional to the force applied to the slave robot in the remote side, it is called master-impedance. While if the master robot is commanded in force, i.e., the force applied by human is measured (and the slave robot is asked to follow that force), and the human operator is provided with change in position/velocity proportional to the position/velocity of the slave robot or proportional to the force applied to the slave robot, this is called master-admittance. On the slave side, slave impedance is a scheme in which the slave robot is asked to apply force to its environment this causes changing its position/velocity, e.g., consider pushing a spring with a certain force. And, slave admittance is a configuration that the slave robot is commanded in position/velocity and due to this motion a force from its environment is applied to it, e.g., consider a certain displacement of a spring. Based on these definitions we can express four types of teleoperation schemes:

- ◇ master-impedance, slave-impedance
- ◇ master-admittance, slave-impedance
- ◇ master-impedance, slave-admittance
- ◇ master-admittance, slave-admittance

Considering the diversity of teleoperation schemes, first question that comes to mind is this: which one is better? And the next logical question will certainly be: how good is it? Answering the first question is difficult. It needs experience and experiments, and there might be more than one proper scheme for a task. On the other hand technological constraints are also limiting the number of choices. Problems like bandwidth of the device and their maximum power, of most of haptic devices⁵ might affect your opinion

⁵haptic devices are very common master robots, that will be introduced in the next chapters more in details.

on choosing the appropriate scheme, or if you have firmly decided to choose a way you may need to build also the corresponding master robot [11]. The ability and functionality of the slave robot can also influence the way you build the teleoperation system. For example it might not be possible for the robot to track both position and force, thus 3-channel and 4-channel approaches will be out. In this Thesis, we use 2-channel bilateral teleoperation architecture with master-impedance, slave-impedance teleoperation scheme. The "2-channel bilateral teleoperation" is satisfactory because it allows to command the slave robot(s) in either position or force, and allows to provide the human operator with force feedback. The "slave-impedance" choice is in line with the slave robot(s) task definition, which is position control of the slave robot in free flight and force control by internal position control in contact with the environment in single robot approach, or position control of the manipulated object in cooperative manipulation approaches. Based on the slave robot(s) task definition the "master-impedance" approach is the best, as the human operator can command the robot intuitively, and feel the force of the remote environment. Moreover, physical properties of our master robot (small torques compared to the human operator force, and with force sensing) suggests the master robot to be used in impedance mode.

To answer the second question four objectives are introduced, in the telerobotics literature, in order to evaluate a teleoperation system[12].

- ◇ **Robustness:** the capability of the controller to stabilize the system in the presence of existing uncertainties of the system, including parametric uncertainties and unmodeled dynamics, external disturbances, communication delays, and communication channel problems such as packet loss.
- ◇ **Task performance:** the efficiency of the slave robot in performing the assigned task, which for example can be applying a force vector, moving to a certain point or with a certain velocity.
- ◇ **Tele-presence:** also referred as feeling of presence is a subjective qualitative criterion that is related to the feeling of the operator that to what extent he/she feels being in the remote side. It is directly related, but not limited, to the quality of haptic feedback that the user is provided with. Visual and auditory feedback are also have important roles in improving this feeling.
- ◇ **Transparency:** An ideal teleoperation scheme works such that the slave robot behaves exactly like the master robot, and the human operator feels exactly what the slave robot feels. In fact, in this ideal condition the human should feel that he/she touches the remote environment, which means to cancel out the master and slave dynamics [9]. This objective is in contrast with robustness.

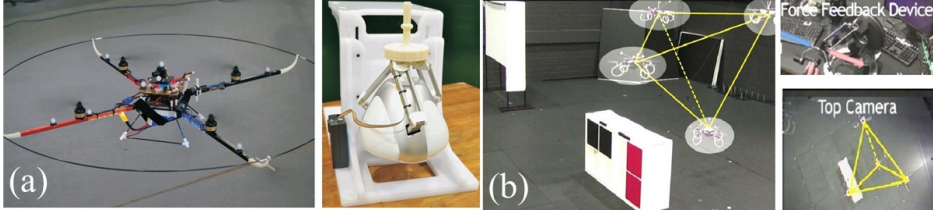


Figure 1.2: Examples of works in bilateral teleoperation of aerial vehicles. (a) Teleoperation of a single vehicle with a customized haptic device [13], (b) Teleoperation of a team of aerial vehicle in formation control [14].

There are some successful developments of different teleoperation schemes for aerial robots in the recent years (Fig.1.2). Most of these schemes have utilized the haptic feedback to increase the operator's situational awareness for collision avoidance in the remote side. Since in this Thesis we aimed a controlled physical interaction between MRAR and its environment, haptic feedback will not be limited to pursue an obstacle avoidance goal.

1.3 Cooperative Manipulation

When it comes to manipulation, there are countless number of dexterous robotic arm manipulators that can handle manipulation tasks with sub-millimeter precision, albeit in structured environment. The story of precise manipulation is true when the manipulated object is small and its weight is less than the maximum payload of the robot, and the required movements are slow and fit in the robot workspace. But, what could be the solution for objects heavier than the maximum payload of the robot? Or when the object is bulky? Or when the object is so long that can vibrate while moving? An immediate solution that comes to mind is to use a bigger and stronger robot. This solution works if you know that your robots always works with object in this range of weight and volume; this is what is going on in packing and storage industries. By the way for Multi-Rotor Aerial Robots, making it bigger means everything must scale up: air-frame, motors, battery. Then the agility of the robot decreases [15], along with the possibility to access narrow places. Moreover, working with a big aerial robot is very dangerous. Furthermore, for very bulky and/or long objects, using a bigger robot will not solve the problem. Thus, for these kind of situations, in unstructured environment, more than a single robot is needed.

Cooperative manipulation is to manipulate a common object by two or more robots. There are two very close concepts in robotics manipulation that might be useful to clarify and distinguish between them: Grasping and Cooperative manipulation.

- ◊ **Cooperative manipulation:** deals with tightly grasped object, by two or more separate robots, usually arm manipulators, which can be also installed on a body of humanoid robot or on a mobile robot base. In cooperative manipulation all of the force/torque components generated at the robot end-effector are transmitted to the manipulated object. In cooperative manipulation the real concerns are: load distribution, interaction forces between robots and manipulated object, and robust holding of the object. Cooperative manipulation is usually considered as a dynamic task in analysis and synthesis of the controllers, because the aim of the system is usually to move the object around [16].
- ◊ **Grasping:** the usual usage of this term is when the manipulated object is held by a multi-fingered robotic hand. In grasping, depending on the contact types, only some components of the fingers' force/torque are transmitted to the object. In grasping, the greatest concern is to keep the contact in the presence of slippage and external force/torque. In grasping, static analysis and synthesis of the controller are acceptable, because most of the time, due to the small workspace of the fingers that are all attached to a palm, the goal of the task is only to hold the object, and the motion is performed by a robotic arm to which the multi-fingered hand is attached. However, dynamic analysis and synthesis of the controller is necessary when the agile action by fingers are required, and when the fingers are to move the object in their workspace [17].

Deploying Multi-Rotor Aerial Robots, equipped with arms either passive or active, for cooperative manipulation and grasping is a very interesting approach, because of the large attainable workspace. In this Thesis, we deal with both concepts cooperative manipulation and grasping. As we shall see in Chapter 3 dynamic grasping is used to design the controller for cooperative aerial manipulation of an object that might lose its contacts with the quadrotors, and in Chapter 4 cooperative manipulation is used to design the controller for a heterogeneous team of grounded arm and quadrotors to manipulate a tightly grasped object. However, by small modifications in the system constraints definition, the proposed control framework covers both of them coherently. So, throughout the Thesis we might use grasping and cooperative manipulation interchangeably.

There are two general types of control approaches for cooperative manipulation:

- ◊ **Centralized controller:** it is a unit controller that has access to the sensor data of

all the robots, and command them all, based on the object and robots' states. In this scheme there is no exchange of information between robots.

- ◇ **Decentralized controller:** there is a local controller on each robot, and each robot decides its own actions based on commands from its own controller, that has access to its own sensor data, sometimes object states, and also exchanges information with some of other robots.

In this Thesis, we use the centralized control approach for cooperative manipulation, because centralized control approach is perfect when the number of the robots are few and it is possible to have the states of all the robots and command them all from a single base station, while decentralized approach is much more suitable when the number of the robots is relatively high and/or is not possible to access all the robots information at the same time and/or is impossible to command them simultaneously. In centralized control approach for cooperative manipulation there are a numerous control techniques, which have been used for robotic arms and also mobile manipulators, ranging from simple proportional-derivative controller to impedance/admittance controllers and also robust and adaptive techniques [16]. However, this Thesis presents one of the first attempts to a real cooperative manipulation with MRARs. Cooperative manipulation is a very challenging area when it comes to MRAR because of the following reasons:

- ◇ **Mechanically underactuation property** of MRAR make it more difficult to apply the desired force/torque— in a short time— such that the object moves in the desired direction, and at the same time the robots (that hold the object) keep stable flight condition. In fact, the mechanical underactuation property of this robots leads a slow dynamic in generating the force components in horizontal plane. Moreover, in most of the cases like quadrotor, only four Degrees of Freedom (DOF) are controllable independently, and some of them, for instance yaw motion, is intended to keep the whole system configuration. Thus, unlike arm manipulators that can apply a full dimensional force/torque vector to the object, we cannot apply more than three components of force. The situation, as we shall see in the next chapters, is even worse: this three dimensional force are severely constrained by mechanical properties of the system.
- ◇ **Aerodynamic disturbances** when the robots are flying close to each other, especially when they have grasped a common object— which demands their rotors to rotate even faster— they impose on each other a strong turbulent aerodynamic disturbance. This will deteriorate the precise control of the robots dramatically which needs to be solved by efficient and well-tuned controllers. The degraded position control of the robots (that are working close to each other) causes a big

uncertainty in the planned grasp. Also during the flight the desired forces to be generated by each robot is subject to strong turbulent disturbances.

To solve this first problem, under-actuation and other limits that comes from it, an optimization problem is defined that its minimal output solution, three dimensional force vectors that satisfies the constraint of the system, are assigned to each aerial robot. Then an efficient attitude and thrust controller is utilized to bring the quadrotor to the desired orientation with the desired motor speeds that will generate the desired force vector. For the second problem, aerodynamic disturbances, efficient and well-tuned controllers are used, and by trying to reduce the robot weight, which leads to a slower rotational speed of the rotors, the turbulent aerodynamic disturbances are reduced.

In the past few years, there have been some successful cooperative aerial transportation such as the ones reported in the Fig. 1.3 by different mechanisms such cables or robots directly attached to the object. To the best of our knowledge this Thesis present the first theoretical and practical implementation of cooperative aerial manipulation by passive arms.

1.4 Related work

In this section a brief review of related work to the context of the Thesis is provided. We first consider the research works for single aerial manipulators, and then we review the works related to cooperative aerial manipulation.

In the last decade, small size MRARs have been a fundamental research topic in the robotics and control domains. In particular, quadrotors have been widely used for aerial photography, surveillance, and inspection [21, 22]. There are numerous practically effective position control approaches for indoor and outdoor applications [23, 24, 25, 26]. Moreover, trajectory tracking [27], path planning and following [28, 29] and higher levels of control such SLAM [30, 31], and formation control [32] are well investigated.

However, the potential capability of MRARs is beyond the above mentioned sensing oriented applications; they can be utilized for aerial transportation [5], or to act on their environment [33, 34, 35]. Physical interaction with the environment, opens the possibility of using UAVs in variety of civilian applications, such as agriculture [36], maintenance [37], construction [38], and Urban Search and Rescue [2]. In fact, there has been a great interest to aerial robots with physical interaction in the past few years and many large scale research projects are active in this context [39, 40, 41, 42].

Interaction with environment using MRARs may mainly be categorized into: using active manipulators and using passive tools. In the first group (using active manipulators),

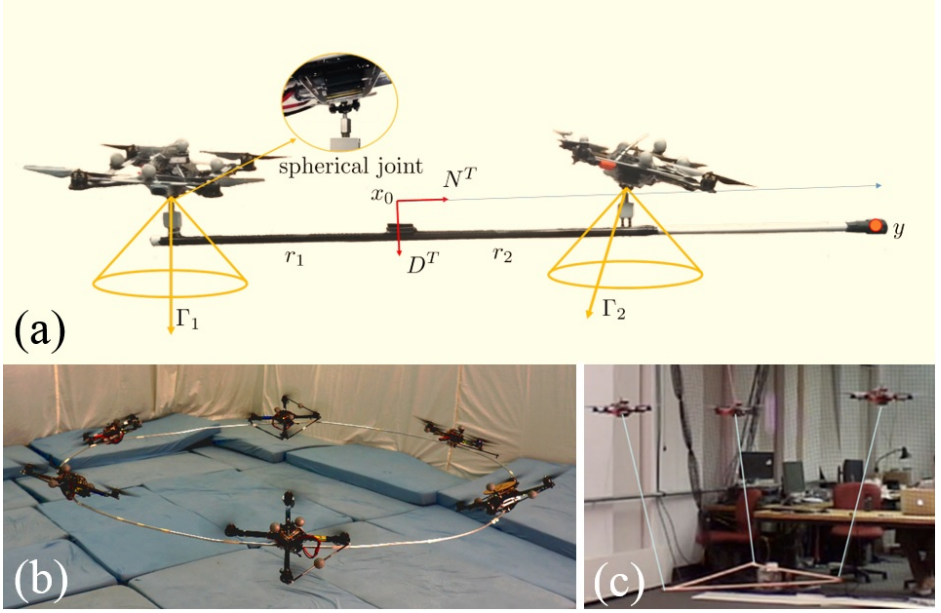


Figure 1.3: Examples of similar works in cooperative aerial transportation with quadrotor helicopters: (a) Aerial tool operation system using quadrotors as rotating thrust generators [18], (b) carrying a flexible payload with multiple flying vehicles [19] (c) cooperative transport with multiple aerial robots with cables [20]

a small parallel manipulator, installed on one side of a MRAR, is used by [43] in order to apply force to environment, and in [44] two serial manipulators are installed below the vehicle that allows to grasp objects. A visual servoing control approach is suggested by [45] to control a quadrotor equipped with a serial manipulator, and a passivity-based adaptive controller which can be applied on both position and velocity control is utilized in [46] to guide a quadrotor equipped with a multi-degree of freedom manipulator. And, in [47] a team of quadrotors, equipped with serial manipulators, is controlled by a visual servoing technique.

In the second group (using passive tools), one of the first attempts in aerial manipulation using passive tools is presented in [48], where based on a kinematic scheme a quadrotor is used to push a cart on rails. A hybrid pose/wrench control framework for quadrotor UAVs is presented in [49], which allows direct contact of the quadrotor body, without any tool, with its environment. Later on in [50] a hybrid force/motion control for tool operation of quadrotors is presented. It is worth noting that [49, 50] control schemes

is based on decoupling of applied force and motion, while we consider friction to keep the contact, and for this reason we use a parallel (and not hybrid) position/force control approach on the slave side.

A standard near-hovering controller is used in [51] to control a quadrotor equipped with a rigid tool attached to it in both free flight and in contact with environment. This controller uses a mapping between the desired vehicle attitude and the commanded force. Planning and control for an aerial robot in contact with its environment for inspection purpose is presented in [37], which switches between different controllers for free flight and in contact. And, in [52] a passive tool with compliant mechanism at the connection point to the vehicle is designed to apply force to the environment.

The usual limitations for those applications are the limited payload of small MRARs [53] or the complexity of bigger unmanned aerial vehicles [54]. Moreover, the typical underactuation of such aerial platforms restrains the variety of possible achievable tasks. Furthermore, for small size quadrotors the trade-off between agility and ability to carry the large and heavy objects suggests a team of aerial robots. Regarding the mechanism, cooperative object transportation, grasping, and manipulation can be categorized into: without tool [19, 55, 56], with rigidly attached passive tools [57], with ropes [58, 59], and with robotic manipulators [60].

Carrying a flexible payload with multiple flying vehicles is presented in [19], where one degree of freedom is considered in attaching quadrotors to the flexible object. The authors proposed a control strategy for guiding the flexible payload to a desired pose, while regulating the deformation modes. Grasping with multiple quadrotors, without tools, has been investigated theoretically in [55], while in [56] multiple quadrotors connected to a tool by spherical joints are used to perform tool operation tasks, where the authors show that using the spherical joints to connect to the object, the attitude dynamics of robots is decoupled from the tool dynamics. Dynamics, control, and planning for cooperative manipulation of payloads suspended by cables from multiple quadrotors is demonstrated in [59]. Then, based on inverse kinematics, a more solid formalism of cooperative transportation using ropes with multiple aerial robots is presented in [58]. Motion planning for 6-D manipulation with aerial towed-cable systems is investigated in [61].

A hierarchical control scheme to grasp and manipulate an object using a team of quadrotors equipped with robotics manipulators has been presented in [60]. For a user specified desired behavior, e.g., trajectory tracking, compliant interaction, the required force is obtained and optimally allocated to the robots. For the same problem, cooperative transportation, cooperative impedance control is presented in [62], and path planning and control is presented in [63]. Aerial object manipulation with rigidly attached tools was

firstly presented in [48], where the authors investigated pushing a cart machine using two quadrotors theoretically, and experimented with a single quadrotor. The idea of formation of Unmanned Aerial Vehicles (UAV) for cooperative aerial tele-manipulation using quadrotors equipped with rigidly attached tools, tracking the human hand fingertips, considering the necessary kinematic mapping has been referred to as *Flying Hand* in [57].

A fleet of small MRARs used as a flying crane has been demonstrated in [64], the dynamics of the load is taken into account and the total wrench produced by the MRARs is significantly higher. More toward the aerial manipulator paradigm, the use of a group of small MRARs to carry a tool and use it to physically interact with the environment has been proposed in [65]. Those approaches consider autonomous fleet of homogeneous underactuated vehicles, resolving the under actuation limitation, but the small payload and endurance issues remain.

Although there are significant achievements in fully autonomous control of small size aerial vehicles [66], poor problem solving capabilities, inadequacy to unexpected environmental changes [67], and legal restrictions⁶ make it convenient to put human operator in the loop, hence feeding back meaningful system information via a haptic device would improve performance. It has been shown in [68] that haptic feedback can improve the operator confidence, and consequently their performance, in real scenarios. Till now the haptic teleoperation with aerial vehicles has been performed mainly for aerial vehicles in free flight, without physical interaction with their environment and mainly to avoid obstacles. The main purpose of the presented works were to let human operators know about the situation and states of the vehicle using haptic feedback. A generic hierarchical passive teleoperation control architecture presented in [69] resulted in a better precision and overall task performance. And, haptic feedback is deployed to avoid obstacles in [70]. Haptic feedback is also widely used to improve the performance in interaction with robot swarms[71].

1.5 Motivation, Objectives, and Contribution

Upon reviewing the essential ingredients in the context of the Thesis, the main motivations for this Thesis, what are the objectives of this research effort, and how and to which extent they were achieved, are introduced in this section.

⁶See, e.g., www.faa.gov/uas.

Motivation

Every year countless number of natural and human-made disasters around the world are registered. After the disaster the search for still alive victims trapped in ruined man-made structures who need to be rescued starts, and the probability of rescuers losing their lives trying to save victims in those catastrophic conditions is too high. Thanks to the growth of technology, the number of death of fire fighters has reduced significantly [72]. Human-robot teaming in Urban Search And Rescue (USAR) is a solution to save more human lives of both victims and rescuers in these situations. The use of robots for search and rescue missions is widely known as rescue robotics, and finding victims in a disaster scenes is the main goal of rescue robotics. Human-robot teaming in USAR is one of the fields where the importance of planning, control, and human robot interaction emerges. The presence of human is essential to cope with robots imperfections in sensing, reasoning, and planning. Moreover, it has been shown in [73] that having a human operator in the backstage of the rescuer robot improves the comfort of disaster survivors. The world trade center disaster was the first known successful of human-robot teaming in USAR [74].

The usual control approach of Human-Robot teaming in USAR is tele-operation control, i.e., a human operator remotely drives a single mobile-manipulator robot in the disaster scene and inspects the remote environment from one or more cameras mounted on the robot. So far the core of the rescue robotics has been mobile manipulators, and only recently MRARs have been used in USAR although limiting to visual inspection. However, the potential capability of MRARs is beyond this sensing oriented application; they can be utilized for aerial transportation, or to act on their environment using passive tools, or robotic manipulator installed on them.

When dexterous manipulation by MRAR is not needed, i.e., when the robot is intended to apply only desired force vectors, e.g., for shutting down an emergency-shut-down key, a lightweight passive tool, is preferable over an active arm manipulator for the following reasons. First, using a simple 1-DoF gripper mechanism, the robot can use lightweight passive tool for holding and moving objects. More complex manipulation are then possible by cooperation of a robot team, which certainly can tolerate a bigger load than a single MRAR. A lightweight passive tool has a small payload footprint, thus less energy is required and the flight time increases significantly, compared to the case of using heavier active arm manipulators. Moreover, a passive tool has a simpler mechanical structure compared to actuated manipulators, so instead of designing a special vehicle to carry and utilize a robotic arm, one can keep the existing simple aerial robot platforms by taking advantage of simple lightweight passive tools. Thus, using passive tools is much more cost-effective in term of design, development and maintenance. Applying forces

using a passive tools also leads to simpler control schemes.

However, robotic (mobile) manipulators usually have significantly higher payload capacities than typical small size MRARs, thus robotic manipulators can remain the core of rescue robotics in many cases. Nevertheless, due to the complexity of the robotics tasks in those situations, e.g., imagine a ruined place due to earthquake, it is quite likely that the robot has to grasp, manipulate and move objects. Many of these objects might not be small enough to be grasped from their central part, or their central part might not be accessible, so the robot has to grasp the object from one end/side. In this case considering the limited manipulator joint torques (especially wrists weakness) manipulating those big/long objects will not be possible in a sufficiently precise manner or even not at all. A similar situation, when the USAR team wants the robot to carry a long tool to perform some special tasks, e.g., opening a window in the ceiling for smoke excavation. In all those cases there will be difficulties in manipulation if the object is not grasped from its central part. On the other hand, if the robot grasps the tool from its central part, the reachable workspace of the tool will reduce to half. Moreover, the robot might need to move objects heavier than its rated payload. Finally, when it comes to manipulating long objects, most of them are flexible enough to degrade the performance of manipulation so much that might lead to failure of the task. For this reason we also propose to use MRARs to help the robot manipulator to overcome the aforementioned issues of: limited payload, limited joint torques, limited workspace, and vibration. We use an MRAR, or when necessary a fleet of them, to help the robot manipulator to overcome the above mentioned deficiencies.

Interestingly those examples could be transposed in industry for the moving of assembly parts in restrained space or for temporarily extension of the workspace. Although the challenges are presented in the context of USAR, the same applies in industrial environments where robotic manipulator could benefit from the extra-dexterity and capabilities induced by a team of flying manipulators.

Objectives

To reach the ambitious goal of utilizing MRAR in USAR and industrial applications, this research work tackles four challenging objectives, advancing the state of the art in robotics science from respective perspectives.

- ◇ **Objective A.** To design new bilateral teleoperation control feedback strategies for position and force control of MRAR equipped with passive tool in physical contact with environment.
- ◇ **Objective B.** To design new bilateral teleoperation control feedback strategies for

cooperative aerial manipulation with a team of MRARs.

- ◇ **Objective C.** To design new control feedback strategies in order to effectively realize a working Heterogeneous Multi-Robot system.
- ◇ **Objective D.** To build a new generation of lightweight passive robotic tool for small size aerial robots.

Contribution

Based on the motivations and objectives of the Thesis, the main contributions of this Thesis are hereby listed.

- ◇ A parallel position/force control in bilateral aerial tool operation of MRAR is successfully designed and implemented.
- ◇ A bilateral tele-operation scheme is designed and implemented for cooperative aerial manipulation in which a human operator drives a team of MRARs, that grasped an object, and receives a force feedback depending on the state of system.
- ◇ A heterogeneous multi-robot system composed of multiple aerial and ground manipulating systems are introduced along with its modeling and control system.

Since the beginning of rescue robotics, a human operator has been in charge of driving and controlling the robot functionality through the on-board cameras of the robot. We will use this strategy with the following differences:

- ◇ **team control:** once the robot manipulator and the MRARs grasped the object, the operator commands the team as whole. More precisely, the human operator is able to command the robots to grasp the object, and give the online desired trajectory of the object by moving a tele-operation device handle;
- ◇ **haptic feedback:** The human operator is provided with haptic feedback, in the force form, to increase his/her situational awareness of the remote site.

The type of information carried by haptic feedback consists of:

- ◇ **obstacle avoidance:** which pushes back the operator's hand when the operator command brings the system close to an undesired collision with obstacles;
- ◇ **tracking error:** a spring-damper-like resistance behavior of the device handle depending on the tracking error in the remote side, that prevents the human operator from commanding trajectories beyond the robot (team) capability;

- ◇ **interaction force:** a force feedback representing the physical interaction with the remote environment as measured by force/torque sensors in the case of physically interactive tasks.

What have been performed in this Thesis with respect to similar works, will be deliberately reviewed in each chapter. However, to have a big picture, it can be summarized in the following main points:

- ◇ the usage of lightweight passive arms instead of heavy actuated manipulators for aerial manipulation;
- ◇ new bilateral teleoperation scheme for parallel position/force control in aerial contact interaction using passive tools;
- ◇ new bilateral teleoperation scheme for cooperative aerial manipulation using passive tools;
- ◇ new configuration of aerial and ground robot manipulation and corresponding control scheme for it.

1.6 Outline of the Thesis

Having reviewed the background, motivation, objectives and contribution of the Thesis in the present chapter, the rest of the Thesis is organized as follows.

In Chapter 2 the problem of parallel position/force control in bilateral aerial tool operation of a quadrotor MRAR is investigated. A lightweight passive tool, composed of a rigid link and a compliant joint at the end-effector is designed, developed, and installed on the quadrotor to enable the vehicle in applying desired force vectors. The proposed bilateral teleoperation scheme enables the human operator to drive a quadrotor using a unified controller in free flight and in contact interaction. In contact-free flight the desired velocity of the robot, in an unlimited workspace, is specified by the position of the limited-workspace master device. The master device position during the contact interaction is instead interpreted as desired force to apply to the environment. The desired position and force are blended by a parallel position/force controller in which the force is regulated by a PI-controller that augments the desired position commanded by the operator with corresponding additional position reference. The contact maintenance is considered by keeping the commanded force vector in the friction cone. The human operator is provided with force feedback depending on the position error in free flight and on the force error in contact. Experimental validation with fixed and moving objects illustrated

the effectiveness and high performances of the proposed scheme in both position and force tracking. And, the system's ease of use for non-trained users and the importance of haptic feedback in improving the performance of the users has been depicted through human/hardware in the loop simulation studies.

Then in Chapter 3, a bilateral tele-operation scheme for cooperative aerial manipulation is proposed in which a human operator drives a team of MRARs, that grasped an object beforehand, and receives a force feedback depending on the state of the system. A rigid tool attached to the vehicle through a passive spherical joint, equipped with a simple adhesive mechanism at the tool-tip that can stick to the grasped object. Having more than two robots, we use the extra DoFs to find the optimal force allocation in terms of minimum power and forces smoothness. The human operator commands desired trajectory of the object for the robot team through a haptic interface. Then an object pose controller, specifies the desired total wrench to be applied to the object by the MRAR team. The system constraints, *e.g.*, MRAR limited forces and contact maintenance, defines the feasible set of forces. Then, the output of the pose controller along with system constraints define the constraints of an optimization problem that allocates forces by minimizing a cost function of forces and their variation. Finally, propeller thrusts are computed by a dedicated attitude and thrust controller in a decentralized fashion. Human/Hardware in the loop simulation study shows efficiency of the proposed scheme, and the importance of haptic feedback to achieve a better performance. And finally experiments with two quadrotors grasping and transporting an object illustrated the feasibility of the proposed bilateral tele-operation scheme for real scenarios.

In Chapter 4, we lay the foundation of the first heterogeneous multi-robot system of the Multiple Aerial-Ground Manipulator System (MAGMaS) type. A MAGMaS consists of a ground manipulator and a team of aerial robots equipped with a simple gripper manipulator the same object. The idea is to benefit from the advantages of both kinds of platforms, *i.e.*, physical strength versus large workspace. The dynamic model of such robotic systems is derived, and its characteristic structure exhibited. Based on the dynamical structure of the system a nonlinear control scheme, augmented with a disturbance observer is proposed to perform trajectory tracking tasks in presence of model inaccuracies and external disturbances. The system redundancy is exploited by solving an optimal force/torque allocation problem that takes into account the heterogeneous system constraints and maximizes the force manipulability ellipsoid. Simulation results validated the proposed control scheme for this novel heterogeneous robotic system. We finally present a prototypical mechanical design and preliminary experimental evaluation of a MAGMaS composed by a KUKA LWR4 and quadrotor based aerial robot. MAGMaS might be used in either fully autonomous system, teleoperated, or shared control manner.

In order to focus on characteristic properties of the robotic team on the remote side, the system is introduced as an autonomous system. The extension to bilateral teleoperation approach is straightforward by adapting the teleoperation scheme of Chapter 3. Teleoperation and shared control approach of MAGMaS, that we call it Tele-MAGMaS, is a practical approach to tackle applications in unstructured environments such as search and rescue missions and logistics, while the fully autonomous system might be used in construction and assembly.

The concluding remarks and possible opportunities for future works are outlined in Chapter 5.

Bilateral Parallel Position/Force Teleoperation of a Quadrotor

2.1 Introduction

Aerial manipulation opens a new era in aerial robotics, in which aerial robots (or teams of aerial robots) act on the environment either by active (actuated) robotic arm manipulators or by passive (non-actuated) tools. When dexterous manipulation by the robot is not needed, e.g., when the robot is intended to apply a desired force vector on the environment in order to push, inspect, or probe its surface, the use of a lightweight passive tool is preferable to a heavier active arm manipulator. Furthermore, using a simple gripping mechanism as, e.g., a magnet or 1-DoF gripper, the robot can use a lightweight passive tool for holding and moving objects. If needed, more complex manipulation are even made possible by a robot team in cooperative tasks [75].

A Lightweight passive tool imposes small payload to the robot, thus less energy is required and the flight time increases significantly, compared to the case of using active arm manipulators. Moreover, a passive tool has a simpler mechanical structure compared to actuated manipulators, so instead of designing a special vehicle to carry and utilize a robotic arm, one can keep the existing simple platforms by taking advantage of simple lightweight passive tools. Thus, using passive tools is much more cost-effective in term of design, development and maintenance. Applying forces using a passive tools also leads to a simpler control scheme. Specially, for quadrotor type MRARs, as we shall see, one can keep the common existing position controllers and augment them for force control.

In this chapter, we propose and experimentally validate a bilateral teleoperation control framework for parallel position/force control of a quadrotor UAV, equipped with a lightweight passive tool, physically interacting with its environment (Fig. 2.1). To maintain the stability [76] during physical interaction, the tool is rigidly attached to the top of the quadrotor. Furthermore, the end-effector (tool-tip) is equipped with a mechanical damper on its surface to facilitate a smooth transition phase from free flight to contact interaction and a passive compliant spherical joint to ensure a good and almost

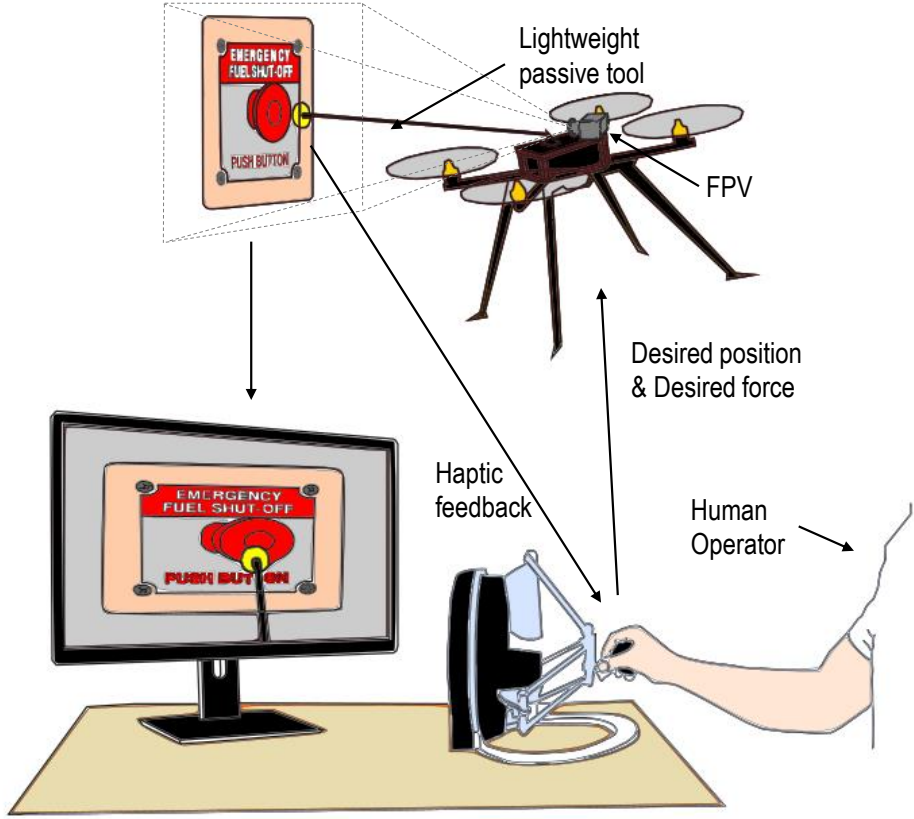


Figure 2.1: Bilateral parallel position/force teleoperation of an aerial robot equipped with a lightweight passive tool in an illustrative search and rescue mission where the robot is tasked to press an emergency shut down push button.

constant friction while the quadrotor changes its orientation to track the desired force. This compliant mechanism makes it possible to involve all the robot's degrees of freedom to generate the desired force vector.

The proposed control scheme is unified and there is no explicit switching control strategy between free flight and in-contact conditions. During a free flight, the operator uses a haptic device with limited workspace to control the position of the quadrotor in a virtually unlimited workspace. When the tool is in contact with the environment the human operator commands are interpreted as desired force vectors. Controlling position

in free flight and force in contact is achieved by utilizing a cascaded parallel position/force controller in which a position controller, in an inner loop, commands the quadrotor motors based on the given desired position. The desired position is composed of the position commanded by the human operator and the output of a PI force controller. Specifically, during free flight the robot end-effector desired velocity is specified by the position of the master device. After a contact is established the master device position is interpreted as the desired force vector. To avoid losing the contact, the desired force is always kept in a feasible set that satisfies the friction constraint. It is worth noticing that although the desired position is event-driven, *i.e.*, the desired position is changing based on the contact event detection, the actuator commands are always calculated by the same control law, and unlike switching control strategy approaches, *e.g.*, [77] the control law is not changing.

Parallel position/force control is a well-known control approach in robotics. The stability analysis of position and force control for robot arms, that have the same dynamic model of our quadrotor equipped with passive tool, is presented in [78, 77]. And in particular the stability analysis of parallel approach to force/position control is in details in [79]. Furthermore, the stability of bilateral parallel force/position teleoperation control is shown in [80]. A Lyapunov approach is the core of the stability proof in the aforementioned article, in which using a generalized mass-spring-damper model the force error is also expressed in term of position error. More recent research works in topic, which are more specific to aerial manipulation can be found in [81, 82, 83, 84, 76], where in [81] an adaptive control scheme is presented for quadrotor subject to dynamic changes in its center of gravity, and [82] has focused on stability of zero-dynamics in force control of aerial robots, and in particular ducted fan, and [83] discussed the stability of Helicopters in compliant contact under PD-PID control (similar to our approach). The stability of nonlinear trajectory tracking control of MRARs equipped with actuated robot manipulators is presented by [84]. The important problem of under-actuation of quadrotors in aerial tool operation force control is well investigated in [76]. In this chapter, in order to avoid repetition, we do not present the stability proof, and instead interested readers are encouraged to see the aforementioned sources.

In this chapter, we use force haptic feedback to improve the performance of position tracking in free flight by feeding back a force vector proportional to the position error, and also to reflect the applied force to let the user feel the force in contact interaction. On the master side, the human operator is provided with a force feedback proportional to the position error in free flight, and proportional to the force applied by the robot in contact. An extensive set of experimental results are presented to validate the proposed approach in applying desired forces to both fixed and moving objects. Furthermore,

human/hardware in the loop simulation user studies, accompanied by statistical analysis revealed the effectiveness of the proposed mechanical and control solutions, and illustrated the importance of haptic feedback in improving the performance of users in tele-manipulation tasks.

The rest of the chapter is arranged as follows. Section 2.2 explains the platform, its dynamic model, contact, and constraints. Section 2.3 presents the proposed unified control approach for bilateral teleoperation with a quadrotor UAV. Experimental results of this approach are presented in Section 2.4, human/hardware simulation and user studies are given in Section 2.5 and conclusion remarks are outlined in Section 2.6.

This Chapter is a revised version of the work currently under review [?].

2.2 Dynamic Model

The teleoperation scheme consists of a human operator, a haptic device (master), an MRAR (slave), communication channel between master and slave, and the environment (Fig. 2.4). The MRAR dynamic models, in particular quadrotors, in free flight are fully investigated in the aerial robotics literature [2]. Thus, here we focus mainly on the dynamic model of a quadrotor equipped with a passive lightweight tool in contact with the environment. The tool is connected to the top of the quadrotor rigidly, and a lightweight rigid link ensures enough room between the propellers and the end-effector to allow a safe contact with the environment. A compliant spherical joint connects the lightweight rigid link to the end-effector, and an elastic shock absorber damper along with the compliant joint helps to establish smoother contacts (Fig. 2.2). In the following we assume that the spherical joint rotation is small, so the springs are in their linear region, the weight of the tool is negligible, and the tool links are rigid.

2.2.1 Slave Model

In this section we derive dynamic model of the robot when the tooltip is in contact with the environment. In order to derive the dynamic model of the system let us define the world frame $\mathcal{W} : \{O_{\mathcal{W}}, x_w, y_w, z_w\}$, the body frame $\mathcal{B} : \{O_B, x_b, y_b, z_b\}$ for the robot, and the contact frame $\mathcal{C} : \{O_C, o, t, n\}$ for the contact point, placed at the object (Fig. 2.3). The origin of $\mathcal{B}$, O_B , coincides with the CoM of the robot. Without loss of generality, and for the sake of clarity, we consider that, in the contact moment, the normal vector n is parallel to y_b , and o and t are parallel with x_b and z_b , respectively, with opposite

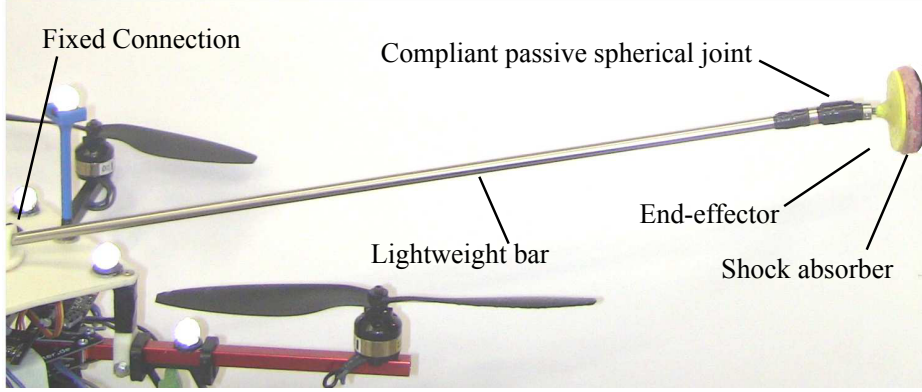


Figure 2.2: The lightweight tool designed to apply a force vector using the quadrotor.

direction, this means that the quadrotor tool is pre-aligned with the object. Moreover, let the axes of $\mathcal{W}$ be coincident with the axes of $\mathcal{C}$, such that $\mathbf{x}_w = \mathbf{n}$.

The position of O_B in $\mathcal{W}$ is indicated with $\mathbf{p} = [x \ y \ z]^\top \in \mathbb{R}^3$, and $m \in \mathbb{R}^+$ and $J \in \mathbb{R}^{3 \times 3}$ are the mass and inertia matrix of the robot, respectively. The orthogonal matrix $R \in SO(3)$ represents the rotation from $\mathcal{B}$ to $\mathcal{W}$. We consider the RPY parameterization of R , i.e., $\boldsymbol{\eta} := [\phi \ \theta \ \psi]^\top \in \mathbb{R}^3$, where ϕ, θ, ψ are the roll, pitch and yaw angles, respectively, and are bounded as $-\frac{\pi}{2} < \phi < \frac{\pi}{2}$, $-\frac{\pi}{2} < \theta < \frac{\pi}{2}$, and $-\pi < \psi \leq \pi$. The angular velocity of $\mathcal{B}$ with respect to $\mathcal{W}$, expressed in $\mathcal{B}$, is denoted with $\boldsymbol{\omega} \in \mathbb{R}^3$. The magnitude of the total thrust acting along the $\mathbf{z}_b$ direction, denoted with $\rho \in \mathbb{R}^+$, and the total moment expressed in $\mathcal{B}$, denoted with $\mathbf{u} = [u_1 \ u_2 \ u_3]^\top$, are the four control inputs of the robot. The end-effector position expressed in $\mathcal{W}$ can be written as

$$\mathbf{p}_e = \mathbf{p} + R\mathbf{d} \quad (2.1)$$

where $\mathbf{d} \in \mathbb{R}^{3 \times 1}$ is the position vector of end-effector in body-frame $\mathcal{B}$ as:

$$\mathbf{d} = \mathbf{d}_1 + \mathbf{d}_2$$

in which $\mathbf{d}_1$ is a vector from the robot CoM to the spherical joint, while $\mathbf{d}_2$ is a vector, with a very small length, from the spherical joint to the contact point, and its direction is perpendicular to the surface, and considering our initial frame convention, $\mathbf{d}_2$ is always along $\mathbf{x}_w$. The following equations describe the dynamics of the robot pose $\mathbf{x} = [\mathbf{p}^\top \ \boldsymbol{\eta}^\top]^\top \in \mathbb{R}^6$

$$m\ddot{\mathbf{p}} + mg\mathbf{z}_w = \rho R\mathbf{z}_b + \mathbf{f}_t + \mathbf{b}_t \quad (2.2a)$$

$$J\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times J\boldsymbol{\omega} = \mathbf{u} + R^\top \boldsymbol{\tau}_r + \mathbf{d} \times R^\top \mathbf{f}_t \quad (2.2b)$$

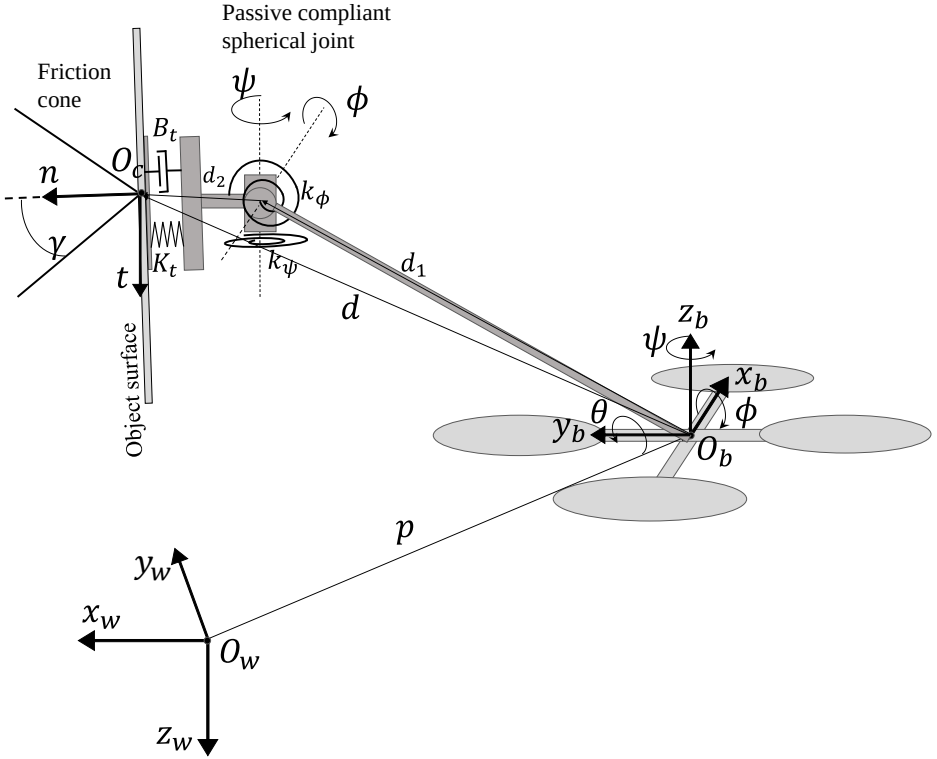


Figure 2.3: The coordinate frames used for the dynamic model derivation of a quadrotor equipped with a passive tool in contact with an object. Notice the presence of a friction cone on the object surface.

in which g is the gravity acceleration constant. The linear spring force and the angular spring torque applied to the end-effector compliant joint are as follows

$$\mathbf{f}_t = -K_t \delta \mathbf{p} \quad (2.3a)$$

$$b_t = -B_t \dot{\delta} p \quad (2.3b)$$

$$\tau_r = -K_r \eta, \quad (2.3c)$$

where $K_r \in \mathbb{R}^{3 \times 3}$ is the diagonal torsional stiffness matrix of the tool's spherical compliant joint, with positive elements $k_\phi, k_\theta, k_\psi \in \mathbb{R}^+$ that are the stiffness elements affected by ϕ , θ , and ψ motions, respectively. $K_t \in \mathbb{R}^{3 \times 3}$ is the diagonal stiffness matrix of the end-effector spring, with positive elements $k_x, k_y, k_z \in \mathbb{R}^+$, respectively.

$B_t \in \mathbb{R}^{3 \times 3}$ is the diagonal damping matrix of the end-effector (shock absorber damper), with positive elements $b_x, b_y, b_z \in \mathbb{R}^+$, respectively. And, $\delta \mathbf{p} = [\delta x \ \delta y \ \delta z]^\top \in \mathbb{R}^3$ is the linear displacement of the end-effector spring.

$$\delta \mathbf{p} = \mathbf{p} - \mathbf{p}_0 + (R - R_0)\mathbf{d}, \quad (2.4)$$

in which $\mathbf{p}_0$ and R_0 are position and rotation matrix of the quadrotor's CoM in the contact moment, i.e., when the springs are in their rest positions. The rotational dynamic equation (2.2b) is expressed in $\mathcal{B}$. To express it in $\mathcal{W}$ we use the relationship between $\boldsymbol{\omega}$ and the derivative of Euler angles $\dot{\boldsymbol{\eta}}$

$$\boldsymbol{\omega} = E(\boldsymbol{\eta})\dot{\boldsymbol{\eta}},$$

where $E(\boldsymbol{\eta}) \in \mathbb{R}^{3 \times 3}$ depends on the orientation order of the rotation matrix R . Thus, (2.2) can be completely expressed in term of generalized coordinates $\mathbf{x}$, as:

$$M(\mathbf{x})\ddot{\mathbf{x}} + \mathbf{b}(\mathbf{x}, \dot{\mathbf{x}}) + K\mathbf{x} + \mathbf{g} = \mathbf{w} + \mathbf{w}_e \quad (2.5)$$

The matrix

$$M = \begin{bmatrix} mI_{3 \times 3} & 0_{3 \times 3} \\ 0_{3 \times 3} & M_{\boldsymbol{\eta}}(\boldsymbol{\eta}) \end{bmatrix}$$

is the inertia matrix in which

$$M_{\boldsymbol{\eta}}(\boldsymbol{\eta}) = E^\top J E \in \mathbb{R}^{3 \times 3}$$

and the vector

$$\mathbf{b} = [(B_t \dot{\mathbf{p}})^\top (C(\boldsymbol{\eta}, \dot{\boldsymbol{\eta}})\dot{\boldsymbol{\eta}})^\top]^\top \in \mathbb{R}^6$$

includes the linear damping and Coriolis/centripetal term of the rotational dynamics in which

$$C(\boldsymbol{\eta}, \dot{\boldsymbol{\eta}}) = E^\top J \dot{E} + E^\top S(E\dot{\boldsymbol{\eta}})J E \in \mathbb{R}^{3 \times 3}$$

with $S(\mathbf{a})$ indicating the skew-symmetric matrix corresponding to a generic vector $\mathbf{a}$; K is the stiffness matrix defined as

$$K = \begin{bmatrix} K_t & 0_{3 \times 3} \\ 0_{3 \times 3} & E^\top R^\top K_r \end{bmatrix}$$

$$\mathbf{g} = [mg\mathbf{z}_w^\top \ \mathbf{0}_{1 \times 3}]^\top \in \mathbb{R}^6$$

is the gravity vector, and

$$\mathbf{w} = [\mathbf{f}^\top \ \boldsymbol{\tau}^\top]^\top$$

is the robot control wrench, and $\mathbf{f}, \boldsymbol{\tau} \in \mathbb{R}^3$ are the robot control force and torque, respectively, expressed in the world frame $\mathcal{W}$ as $\mathbf{f} = \rho R[0 \ 0 \ 1]^\top$ and $\boldsymbol{\tau} = E^\top \mathbf{u}$. And, $\mathbf{w}_e \in \mathbb{R}^6$ is the coupling dynamics between rotational and translational subsystems, as follows:

$$\mathbf{w}_e = \begin{bmatrix} -K_t(-\mathbf{p}_0 + (R - R_0)\mathbf{d}) - B_t \dot{R}\mathbf{d} \\ -E^\top S(\mathbf{d})R^\top(\mathbf{p} - \mathbf{p}_0 + (R - R_0)\mathbf{d}) \end{bmatrix}. \quad (2.6)$$

2.2.2 Contact Model

Considering the *hard finger with friction* contact model [17], the objects does not apply pure torques to the end-effector. To keep the contact point, i.e., to avoid sliding over surface and losing the contact, the applied force by the environment on the end-effector, which of course is the opposite of the force that the quadrotor applies to the environment, $\mathbf{f}_e = [f_o \ f_t \ f_n]^\top \in \mathbb{R}^3$, must balance the forces and torques of the linear and torsional springs on the small link ($\mathbf{d}_2$) of the robot tool. Considering the separation principle let $-\mathbf{f}_e$ be the sum of two components: $\mathbf{f}_f$, which balances to the linear spring force, and $\mathbf{f}_t$, whose resultant torque on the link $\mathbf{d}_2$ is equal and opposite to the torsional spring torque, i.e.,

$$-\mathbf{f}_e = \mathbf{f}_f + \mathbf{f}_t \quad (2.7a)$$

$$\mathbf{f}_f = -\mathbf{f}_t \quad (2.7b)$$

$$\mathbf{d}_2 \times \mathbf{f}_t = -\boldsymbol{\tau}_r. \quad (2.7c)$$

Now recalling our frame convention, we may write $\mathbf{f}_e = [f_x \ f_y \ f_z]^\top$, such that $f_x = f_n$, $f_y = f_o$, $f_z = f_t$, and since $\mathbf{d}_2 = [d_2 \ 0 \ 0]^\top$ we obtain

$$\begin{cases} f_x = k_x \delta x \\ f_y = k_y \delta y + \frac{k_\psi \psi}{d_2} \\ f_z = k_z \delta z + \frac{k_\theta \theta}{d_2} \end{cases}. \quad (2.8)$$

Since the contact is unilateral the normal component of the force must be positive. Furthermore, in order to avoid slippage, the force must remain in the friction cone [17], i.e.,

$$f_x \geq 0 \quad (2.9a)$$

$$\sqrt{f_y^2 + f_z^2} \leq \mu f_x. \quad (2.9b)$$

This constraint, which is based on the Coulomb friction model, has an intuitive graphical representation: a cone with cone angle γ defined as follows:

$$\gamma = \tan^{-1}(\mu) \quad (2.10)$$

where $\mu \in \mathbb{R}^+$ is the friction coefficient between end-effector and object surfaces. Obviously, higher friction coefficients give wider friction cones.

2.2.3 Master Model

The dynamic model of the haptic interface with n_m actuated degrees of freedom, considering activated gravity compensation controller, can be described as

$$M_m(\mathbf{x}_m)\ddot{\mathbf{x}}_m + C_m(\mathbf{x}_m, \dot{\mathbf{x}}_m)\dot{\mathbf{x}}_m = \mathbf{f}_h + \mathbf{f}_c \quad (2.11)$$

where $\mathbf{x}_m \in \mathbb{R}^{n_m}$ is the configuration vector of the haptic interface, $M_m(\mathbf{x}_m) \in \mathbb{R}^{n_m \times n_m}$ is the inertia matrix, $C_m(\mathbf{x}_m, \dot{\mathbf{x}}_m) \in \mathbb{R}^{n_m \times n_m}$ is the Coriolis/centripetal matrix, and $\mathbf{f}_h \in \mathbb{R}^{n_m}$ and $\mathbf{f}_c \in \mathbb{R}^3$ are the human and control forces, respectively.

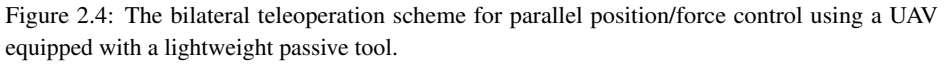
2.3 Control System

The main objectives of the proposed bilateral teleoperation scheme are: 1) position control of the robot in an unlimited workspace using a limited workspace haptic device, 2) contact maintenance, 3) force tracking while in contact, i.e., the quadrotor using its tool applies the user commanded force, and 4) providing the user with force feedback proportional the position error in free flight and the applied force in contact (the haptic feedback in the contact condition is equal to the measured force from the force sensor with the opposite direction.). The overall teleoperation scheme is depicted in Fig. 2.4.

2.3.1 Position Control

Let $\mathbf{p}_d \in \mathbb{R}^3$ be the desired position of the quadrotor CoM. The position control of quadrotor, as a mechanically under-actuated robot, is implemented using a two layer controller where in the inner loop the orientation of the vehicle is controlled and the outer loop provides the inner loop with the suitable desired roll (ϕ_d) and desired pitch (θ_d) to control the robot planar motion. The robot altitude is controlled independently from its latitude (x) and longitude (y), and yaw (ψ) is controlled independently from roll and pitch. The inner attitude control loop is implemented using a PID controller, and also the outer loop for the planar motion is implemented by PID controller, while the altitude is controlled by a feedback linearization controller.

$$\mathbf{u} = K_D^\eta \dot{\mathbf{e}}_\eta + K_P^\eta \mathbf{e}_\eta + K_I^\eta \int_0^t \mathbf{e}_\eta dt \quad (2.12a)$$



$$u_y = k_p^y e_y + k_d^y \dot{e}_y + k_i^y \int_0^t e_y dt \quad (2.12e)$$

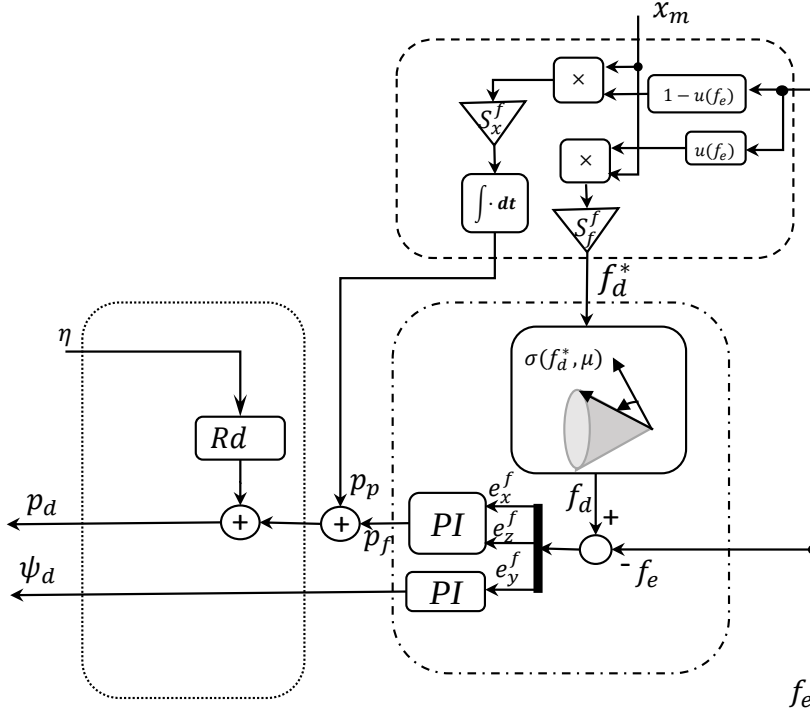


Figure 2.5: Parallel position/force control for a quadrotor UAV equipped with a lightweight passive tool, based on augmenting a position controller with a desired motion coming from the desired and measured forces.

$e_\eta = \eta - \eta_d$ is the orientation error in which η_d is the desired orientation, and $K_P^\eta, K_D^\eta, K_I^\eta \in \mathbb{R}^3$ are the proportional, derivative, and integral diagonal gain matrices with positive elements to regulate the attitude. e_x, e_y, e_z are the elements of position error as $\mathbf{p}_d - \mathbf{p} = [e_x \ e_y \ e_z]^\top$, where $\mathbf{p}_d$ is the desired position of the robot, that is the sum of the commanded position by the human operator and the position corresponding to the commanded force. $k_p^x, k_d^x, k_i^x, k_p^y, k_d^y, k_i^y, k_p^z, k_d^z, k_i^z \in \mathbb{R}^+$ are proportional, derivative and integral gains in x, y , and z axes, respectively.

The position and attitude controllers presented above are concerning the quadrotor CoM. However for our purpose it is necessary to control the end-effector position and

quadrotor CoM orientation. In fact, when the end-effector is in contact with the object its position does not move, while the quadrotor attitude is free to move (to the extent that the compliant passive spherical joint allows), and also the quadrotor's CoM position changes according to its orientation. In fact, if we neglect the contraction of the end-effector surface, i.e., $k_x, k_y, k_z = \infty$ the quadrotor position is free to move over the spherical cap of radius $\|\mathbf{d}\|$.

2.3.2 Force Control

Now consider the master device position $\mathbf{x}_m \in W_m$, where $W_m \subset \mathbb{R}^3$ is the limited workspace of the haptic device. We shall design our system in order to let the human operator use $\mathbf{x}_m$ to control both the quadrotor position in a virtually unlimited workspace (during free flight) and the desired force to apply to the environment (during in contact). The parallel position/force control scheme of the slave side is depicted in Fig. 2.5.

Let us start by defining the following detection function to signal if the robot end-effector is in contact or not.

$$u(\mathbf{f}_e) = \begin{cases} 1 & \text{if } \|\mathbf{f}_e\| > 0 \\ 0 & \text{otherwise.} \end{cases} \quad (2.13)$$

The desired position of the end-effector during free flight is given by integrating the master position as

$$\mathbf{p}_p = \int_0^t (1 - u(\mathbf{f}_e)) S_p^f \mathbf{x}_m dt. \quad (2.14)$$

where $S_p^f \in \mathbb{R}^{3 \times 3}$ is the scaling matrix (the superscript f stands for forward, and the subscript p stands for position.). The desired position of quadrotor CoM can simply be obtained by subtracting the tool distance.

When the end-effector establishes a contact $u(\mathbf{f}_e)$ becomes 1, and thus $(1 - u(\mathbf{f}_e))$ becomes 0, the integral keeps the position of the contact moment, and the motion of the master robot is used to decide the desired commanded force. In order to reduce the number of bouncing of end-effector over the the object surface, in the contact establishing (or docking) phase, a hysteresis block is added to the event detection mechanism, for the experimental evaluation. Since the robot can apply a limited force to the environment, integration of the master position is not necessary. This results also in a fast slave response to the force command. So, the commanded force, $\mathbf{f}_d^* = [f_{dx}^* \ f_{dy}^* \ f_{dz}^*]^\top \in \mathbb{R}^3$, by human operator is

$$\mathbf{f}_d^* = u(\mathbf{f}_e) S_f^f \mathbf{x}_m \quad (2.15)$$

where $S_f^f \in \mathbb{R}^{3 \times 3}$ is the scaling matrix (the superscript f stands for ‘forward’ and subscript ‘ f ’ for force). To make sure that the desired force will not violate the contact maintenance constraint (2.9), the commanded force is modified, if necessary, as follows:

$$\mathbf{f}_d = \begin{cases} \mathbf{f}_d^* & \text{if } \sqrt{f_{dz}^{*2} + f_{dy}^{*2}} \leq \mu f_{dx}^* \\ \sigma(\mathbf{f}_d^*, \mu) & \text{otherwise} \end{cases} \quad (2.16)$$

where $\sigma(\mathbf{f}_d^*, \mu)$ is a function (obtained from the Rodrigues’ rotation formula [85]) that projects the desired commanded force $\mathbf{f}_d^*$ to the surface of the friction cone, that is defined by friction coefficient μ , i.e.,

$$\sigma(\mathbf{f}_d^*, \mu) = \cos(\alpha) \mathbf{f}_d^* + \sin(\alpha) (S(\mathbf{a}) \mathbf{f}_d^*) + (1 - \cos(\alpha)) (\mathbf{a}^\top \mathbf{f}_d^*) \mathbf{a}$$

where $\mathbf{a} = (S(\mathbf{f}_d^*) \mathbf{n}) / \|(S(\mathbf{f}_d^*) \mathbf{n})\|$ is the unit axis of rotation, and $\alpha = \beta - \gamma$ is the rotation angle needed to rotate $\mathbf{f}_d^*$ around $\mathbf{a}$ to project it on the surface of the friction cone, β is the angle between $\mathbf{f}_d^*$ and $\mathbf{n}$, and γ is the friction cone angle. The rotating function σ preserves the desired force norm and applies the minimum rotation to keep it within the feasible force set, defined by the friction cone.

Recalling the coincidence of contact frame $\mathcal{C}$ and the world frame $\mathcal{W}$ we define the force error as $\mathbf{e}_f = \mathbf{f}_d - \mathbf{f}_e = [e_x^f \ e_y^f \ e_z^f]^\top \in \mathbb{R}^3$. An appropriate robot motion is then generated using a PI-controller to implement $\mathbf{f}_d$.

Now according to (2.8), the components of $\mathbf{f}_e$ have clear dependencies to the quadrotor’s states, $\mathbf{p}$ and $\boldsymbol{\eta}$, such that the normal component of the force, f_x , depends on δx , while δy and ψ specify f_y , and f_z depends on δz and θ . So, we can control the normal component of force by commanding the motion along x .

To control f_y , at first glance it seems that we have two variables as control signals: δy and ψ . Due to the under-actuation of the vehicle the latitude change δy of the robot requires pitch motion $\delta \theta$. However, considering the hard finger with friction contact model, roll motion results in rotation around normal axis of the contact frame (i.e., $\mathbf{n} \equiv \mathbf{x}_w$), which is not desirable. Therefore, we choose the yaw motion, ψ , as the control input to regulate f_y , and we consider the forces resulting from the roll motion, which is unavoidable due to the position control actions, as a disturbance.

To control f_z , following a similar reasoning, we choose δz as the control input. This case is more intuitive because by changing altitude command the thrust component is increasing while keeping the orientation fixed. We utilize these control signals by feeding a PI-controller with force errors e_x^f and e_z^f that generates, the desired position $\mathbf{p}_f = [p_x^f \ 0 \ p_z^f]^\top$, and also by feeding e_y^f to a PI-controller which produces the desired yaw motion (ψ_d) of the quadrotor CoM. However, a yaw motion command to the quadrotor’s CoM demands changing the end-effector position.

Summarizing, the desired position $\mathbf{p}_d$ is generated as the sum of the frozen integral of the free flight position control $\mathbf{p}_p$, and the corresponding position to control the forces along $\mathbf{x}_w$ and $\mathbf{z}_w$, i.e., $\mathbf{p}_f$, which must be expressed for quadrotor's CoM (note that $\mathbf{p}_p$ and $\mathbf{p}_f$ are expressed for end-effector).

$$\mathbf{p}_d = (\mathbf{p}_p + \mathbf{p}_f) + R\mathbf{d} \quad (2.17)$$

And, the components of $\mathbf{p}_f$ can be calculated as follows:

$$p_x^f = k_{pf}^x e_x^f + k_{if}^x \int_0^t e_x^f dt \quad (2.18a)$$

$$p_z^f = k_{pf}^z e_z^f + k_{if}^z \int_0^t e_z^f dt \quad (2.18b)$$

$$\psi_d = k_{pf}^y e_y^f + k_{if}^y \int_0^t e_y^f dt \quad (2.18c)$$

where $k_{pf}^x, k_{if}^x, k_{pf}^y, k_{if}^y, k_{pf}^z, k_{if}^z \in \mathbb{R}^+$ are positive proportional and integral gains in the x , y , and z -directions, respectively.

Note that the presented control approach does not depend on the frame choice, since by considering an appropriate transformations it is possible to extend it to any other arbitrary choice of world, body, and contact frames.

2.3.3 Master Control and Haptic Feedback

The input of the master robot (haptic device) is composed of two elements: the human force $\mathbf{f}_h$ and the master control force $\mathbf{f}_c$. The master control force has two main elements $\mathbf{f}_{PD}$, and $\mathbf{f}_{pf}$, notice that for the sake of brevity, the internal gravity compensation of the device is not mentioned here. The term $\mathbf{f}_{PD}$ is a negative proportional derivative term that has two main roles: Firstly, the proportional term is intended to bring back the device to its zero position when the device is not moved by the operator, so that the quadrotor will not move or apply force when the haptic device is released. And, the derivative term, is intended to keep the stability of the teleoperation loop. On the other hand, $\mathbf{f}_{pf}$ is the haptic feedback given to the user depending on the position error in free flight or force error in contact. Summarizing:

$$\mathbf{f}_c = \mathbf{f}_{pf} + \mathbf{f}_{PD} \quad (2.19a)$$

$$\mathbf{f}_{PD} = K_p \mathbf{x}_m + K_d \dot{\mathbf{x}}_m \quad (2.19b)$$

$$\mathbf{f}_{pf} = S_f^b \mathbf{f}_e + (1 - u(\mathbf{f}_e)) S_p^b \mathbf{e}_p \quad (2.19c)$$

where $K_p, K_d \in \mathbb{R}^{3 \times 3}$ are the proportional and derivative positive definite diagonal gain matrices, and $S_f^b, S_p^b \in \mathbb{R}^{3 \times 3}$ are scaling matrices (the superscripts b stand for backward, and the subscripts p and f stand for position and force, respectively).

2.4 Experimental Results

In order to validate the proposed bilateral teleoperation approach for parallel position/force control of quadrotor, a simple lightweight tool with the total weight of 0.05 kg is designed and developed (Fig. 2.2). The tool is connected to the top of the quadrotor rigidly, and a lightweight rigid link provides enough distance from the propellers to the end-effector to contact with the environment. The vector in the body frame $\mathcal{B}$ from the quadrotor CoM to the end-effector surface is $\mathbf{d} = [0 \text{ m}, 0.5 \text{ m and } 0.2 \text{ m}]$. The link lengths are $d_1 = 0.51 \text{ m}$, and $d_2 = 0.02 \text{ m}$. A compliant spherical joint connects the lightweight rigid link to the end-effector, and a shock absorber damper along with the compliant joint help to establish smooth contacts. The end-effector surface is covered by a high friction material to magnify the feasible force vector set. We considered the friction coefficient to be $\mu = 0.55$, whose corresponding friction cone angle is $\gamma = \pi/6$. This value is relatively less than the real friction coefficient value, thus it is a safer choice that ensures not to lose the contact. The quadrotor platform used for the experiments is a Mikrokopter[®] x4 platform (HiSystems GmbH). The weight of the quadrotor, without the tool, is 1 kg. The software is implemented in the ROS-based framework Telekyb2 [86], integrated with Matlab/Simulink[®] to perform control loop at 100 Hz. The position tracking of the robot is performed by a Vicon tracking system (Vicon Capture Systems, UK). The quadrotor thrust and rotational controller is implemented on its onboard microcontroller, based on the inertial sensors of the robot, the rest of the control law is implemented on an external PC communicating with the robot using a pair of Zig-Bee transceiver chips. An Omega.3 haptic device (force dimension, Switzerland) is used as master device. To validate the proposed approach, we used the force/torque ATI sensor (ATI Industrial Automation, USA) embedded inside the object. Interested readers are strongly encouraged to see [49, 87, 88] in order to see the different techniques allowing to replace the sensor with observers. In the first experiment, the user drives the quadrotor to establish a contact with a fixed object and then applies desired forces to the object. In the second experiment the operator drives the quadrotor to establish a contact with a cart and then pushes the cart to move it by one meter.

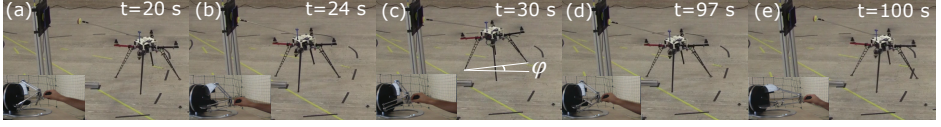


Figure 2.6: Snapshots of the first experiment: dock and apply a commanded time-varying force to a fixed object, (a) The quadrotor in free flight, (b) establishing a contact with the object, (c) applying force vectors, (d) releasing the contact, and (e) in free flight again.

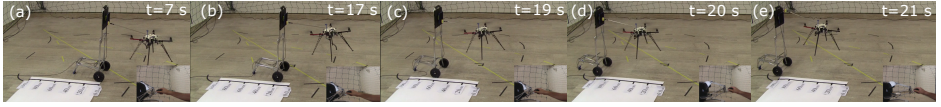


Figure 2.7: Snapshots of the second experiment: dock and apply a commanded time-varying force to a moving object, (a) establishing a contact with the object, (b) applying force vectors and overcome the cart friction with ground, (d) the quadrotor and the cart in an accelerated motion, and (e) releasing the contact and in free flight again.

2.4.1 Fixed Object

In the first experiment, the quadrotor initially located at the origin of the global coordinate, while the CoM of the object (a $0.15 \text{ m} \times 0.15 \text{ m}$ plate) is located at $\mathbf{d} = [1.0 \text{ m}, 0.0 \text{ m} \text{ and } -0.85 \text{ m}]$ with downward pointing $\mathbf{z}_w$. The human operator drives the quadrotor towards the object, and once the robot reaches the object, the driver commands a set of continuous force trajectories, by means of the haptics device, and eventually the driver commands the robot to leave the object, and brings it back to free flight. Fig. 2.6 represents the snapshots of different moments of the experiment, and Fig. 2.8 shows the results of the experiment. Fig. 2.8(a) shows the position tracking during the experiment. As it can be seen, before the contact event, and after the quadrotor leaves the object the position error is small. While during the contact, there is significant position error, specifically in x -direction which corresponds to the normal component of force. In fact, larger position error during the contact with fixed object means asking for higher thrust and more pitched orientation, which results in larger applied forces.

Fig. 2.8(b) shows the contact maintenance function output, which keeps the desired force vector inside the friction cone. It can be seen that, whenever is necessary the normal component of the desired commanded force is increased while the other two tangential component are decreased, and the desired norm of the input ($\mathbf{f}_d^*$) and output ($\mathbf{f}_d$) are equal.

Fig. 2.8(c) shows the force tracking control result, and Fig. 2.8(d) illustrates the force

error norm during the experiment. As it is evident from the Fig. 2.9(c) and Fig. 2.8(d) the force tracking performance is very good (average absolute error of 0.11 N, which represents less than 10% relative error, and maximum absolute error of 0.51 N). The high value of error in the detachment instance can be reduced by using more agile controllers for the inner loop.

The contact transition is shown in a separate window inside Fig. 2.8(c), which introduces a very smooth contact transition with only a small single bouncing event. Note that in the transition phase of robot force control with rigid environment, having a finite number of bouncing and inadvertent loss of contact is common, even for grounded robotic arm manipulators, when the reaching velocity is not zero [89].

The signals related to the master side are shown in Fig. 2.10. The master position (the position of its handle with respect to the center of its workspace) is shown in Fig 2.10(a), as it can be seen all the operation has successfully been performed despite of the limited workspace of the master device. Fig. 2.10(b) shows spring-damper force $\mathbf{f}_{PD}$ that brings back the master device handle to the center of its workspace, and evidently its value are proportional to the master robot displacement. Fig. 2.10(c) depicts the position tracking error, which is the first constitutive component of the haptic feedback $\mathbf{f}_{pf}$, and Fig. 2.10(d) is the applied force to the object $\mathbf{f}_e$, the second constitutive component of $\mathbf{f}_{pf}$, the haptic feedback $\mathbf{f}_{pf}$ is shown in Fig. 2.10(e), and as it can be seen in the in the free flight, e_p has small values, and $\mathbf{f}_e$ is zero, thus the haptic feedback $\mathbf{f}_{pf}$ has a small value proportional to e_p , while in contact the position error increases and the applied force $\mathbf{f}_e$ is also following the desired force and the haptic feedback is proportional to the applied force.

2.4.2 Moving Object

In the second experiment, the robot is initially located at the global frame origin and a cart, with plate of $0.15 \text{ m} \times 0.15 \text{ m}$ attached to it, is located at $x = 0.50 \text{ m}$, and the plate center, which is intended to hold the sensor has an altitude of $z = -0.90 \text{ m}$ with downward pointing z_w . The human operator is driving the quadrotor towards the cart, and once the robot reaches the cart, the driver pushes it until it passes 1.0 m , and eventually the driver commands the robot to leave the object, and brings the robot back to free flight. Fig. 2.7 depicts the snapshots of different moments in this experiment, while Fig. 2.9 shows the results of the experiment.

Fig. 2.9(a) shows the position tracking during the experiment. The difference between

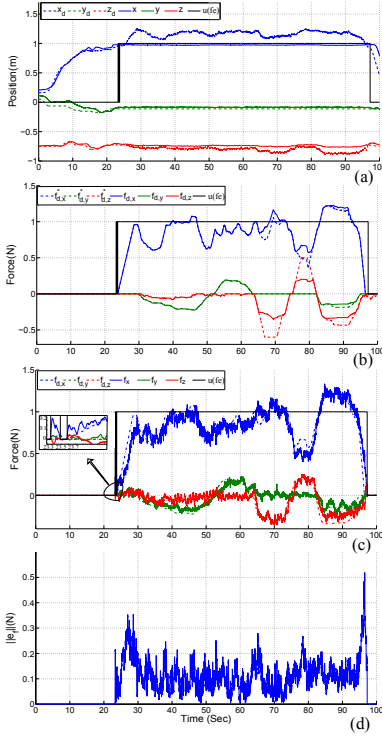


Figure 2.8: First experiment: docking and applying a force commanded by the human operator to fixed object: (a) position tracking, (b) contact maintenance, i.e., keeping of the desired force vector within the friction cone, (c) force tracking, and (d) force error norm.

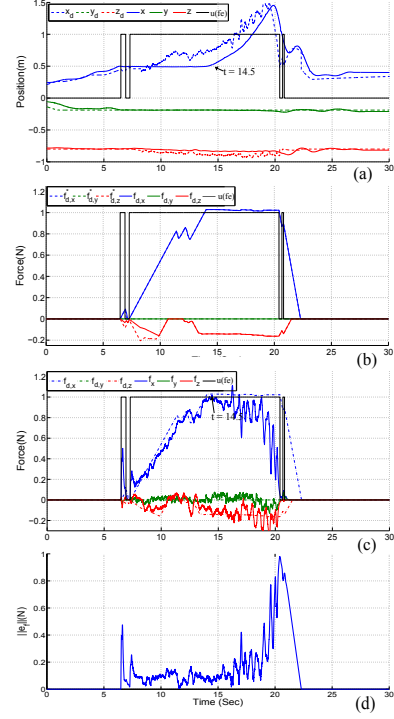


Figure 2.9: Second experiment: docking and applying a commanded force to a moving object (a cart) in order to push it 1 m away: (a) position tracking, (b) contact maintenance, i.e., keeping of the desired force vector within the friction cone, (c) force tracking, and (d) force error norm.

the new situation (a moving object) compared to the previous experiment (a fixed object) can be seen through this plot, where after establishing the contact, while the quadrotor is applying the force to the object (cart), its position is not changing until the time (in this experiment 14.5 s) in which the applied force can overcome the static friction of the cart wheels with the ground. Then, the cart (and the quadrotor too) experiences an accelerated motion.

Fig. 2.9(b) shows the contact maintenance function input and output forces. Since the main purpose is to push the cart, the major component of the commanded force is in the

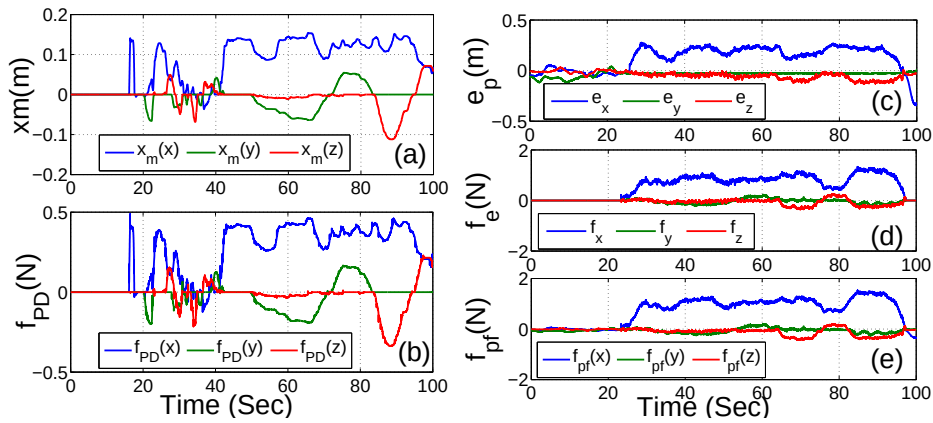


Figure 2.10: First experiment: docking and applying a force commanded by the human operator to fixed object: (a) position of the master, (b) spring-damper force that brings back the master device handle to the center of its workspace, (c) position tracking error, the first constitutive component, and (d) the applied force to the object, the second constitutive component of (e) the haptic feedback f_{pf} .

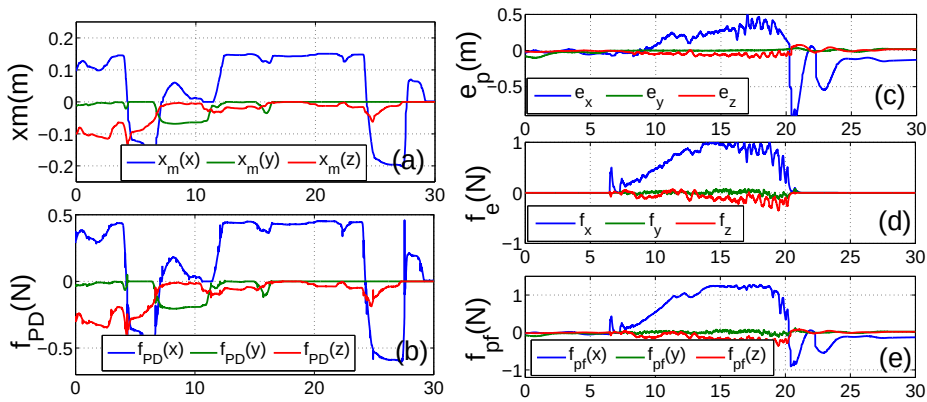


Figure 2.11: Second experiment: docking and applying a commanded force to a moving object (a cart) in order to push it 1 m away: (a) position of the master, (b) spring-damper force that brings back the master device handle to the center of its workspace, (c) position tracking error, the first constitutive component, and (d) the applied force to the object, the second constitutive component of (e) the haptic feedback f_{pf} .

normal direction, thus most of the time the feasible commanded force is the same as the desired commanded force by the human operator, and as it is evident from the Fig. 2.9(c) the contact is kept during the force interaction, even during the cart motion.

The force tracking control results, shown in Fig. 2.9(c), show that this is a more difficult task compared to the previous task (force tracking control in contact with a fixed object). As it can be seen, while the cart is fixed, i.e., when the applied force by the quadrotor end-effector is compensated by friction of the cart wheels with the surface, the force tracking has a similar performance to the previous experiment. While once the cart starts to move the error increases. However, considering the particular application of this experiment, which aims at pushing a cart forward, as far as the contact is kept and driver is able to accomplish the task, the experiment is considered successful, although the average of the absolute force error norm is 0.5 N, more than 20% relative error, and the maximum of the force error norm reaches 0.98 N in Fig. 2.9(d). The large error value in the detachment phase, that is when the human operator see the accelerating cart passed the line push back the handle in order to bring the robot back, can be improved by limiting the integral term of the PI-force controller, and increasing the proportional gain of PI-controller, and also using more agile controller in the inner position controller. It is worth noticing that in this experiment the goal was to evaluate the efficiency the proposed controller in applying force to objects in order to move them in a way the human operator wants rather than precise force tracking.

The signals related to the master side of this experiment are shown in Fig. 2.11. The position of the master device handle x_m is depicted in Fig. 2.11(a). As it can be seen, with a limited workspace (contained in a sphere of 0.2 m of diameter), the slave robot in an unlimited workspace can be controlled in position. Compare to the experiment with fixed object there are some glitch in the f_{PD} that are due to the motion of the target object, this The spring-damper force is shown Fig. 2.11(b). The position tracking error, the applied force to the object, and the haptic feedback are shown Fig. 2.11(c-e). Again we see that the haptic feedback is proportional to the position error in the free flight and is proportional to applied force to the moving object in contact.

2.5 Human/Hardware in the Loop Simulation

In order to evaluate the efficiency of the system and to assess the importance of the haptic feedback in improving the user performance we conducted two between-subject user studies in which human subjects performed manipulation tasks in a virtual environment. For the safety reasons these experiments were performed in a virtual environment. The quadrotor with its passive tool is simulated in v-rep simulator software (Coppelia

Robotics). Simulation of the system, including the physical interaction, is based on bullet 2.78 physic engine, thus represents a realistic simulation results. The control loop was implemented at 100 Hz, and the working frequency of the haptic device (Omega.3), that is connected to the v-rep simulation environment via a customized C++ plugin, was 4 kHz to ensure a smooth performance of the haptic device. The quadrotor properties were identical to the real quadrotor parameters. In addition, the quadrotor was equipped with two cameras: front and below, that both had the angle view of 90° . The first experiment is intended to illustrate the importance of haptic feedback, and the second experiment is designed to show the system's ease of use for non trained users in practical situations.

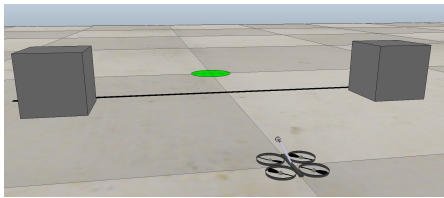


Figure 2.12: Human/hardware in the loop experiments, first experiment, pushing cubes with different weights, with and without haptic feedback.



Figure 2.13: Human/hardware in the loop experiments, second experiment, pushing a door to open it, with and without haptic feedback.

2.5.1 Scenario 1: manipulating objects with different weights

In this experiment, that is intended to show the importance of haptics in improving the precision of manipulation, the quadrotor was initially located at the center of the environment (origin of the global frame), and there were two cubes of size 1 m^3 in the environment placed at $[3\text{ m}, -3\text{ m and } 0.5\text{ m}]$ and $[3\text{ m}, 3\text{ m and } 0.5\text{ m}]$; their appearance were identical to each other, while their weight were different, one of them was 0.2 kg and the other one was 1 kg . Moreover, there were a straight line at $x = 3.75\text{ m}$, and a land mark at $[6\text{ m}, 0\text{ m and } 0\text{ m}]$ on the ground. The mission was to push the cubes to just touch the line, and then land on the landmark (Fig. 2.12). The subjects were asked to perform the task once with and another time without haptic feedback. The initial place of the cubes were exchanged in the two conditions. The users could see the streaming video of two cameras while watching the scene from a fixed point of view. The desired yaw angle of the robot was set to zero in free flight. The subjects were driving the quadrotor by moving the haptic device, and the haptic device motion is mapped to the quadrotor desired velocities. Twelve subjects (eight men, four women, aged 24-33)

participated in the experiment. None of them served in USAR teams before, they had no previous experiences of working with UAVs and haptic devices. The subjects participated voluntarily, and knew that they can leave the experiment any time for any reason. The scene and the functionality of the quadrotor were explained to them, they had enough time to learn how to drive the quadrotor, and then they had one experiment in which the haptic feedback was deactivated, and another experiment with activated haptic feedback, we call these two conditions **NC** and **HC**, respectively. The subjects warned about the possible different weights and places of the objects in the experiments. The criterion to compare the experimental results of two conditions was the total distance of the cubes from the target line in the end of the experiments. The ideal result is zero.

A paired-samples t-test was used to determine whether there was a statistically significant mean difference between the two conditions **NC** and **HC**. Data were mean $\pm$ standard deviation, unless otherwise stated. There was no outliers in the collected data, and the assumption of normality was not violated, as assessed by Shapiro-Wilk's test ($p = 0.293$). Participants performed the experiment of **NC** with the result of $(0.3776 \pm 0.1605 \text{ m})$ that showed a higher error compared to **HC** ($0.1901 \pm 0.1059 \text{ m}$). The paired-samples t-test showed a statistically significant increase of 0.1875 m (95% CI, 0.0780 m to 0.2970 m), $t(11) = 3.770$, $p = 0.003$, $d = 1.09$, in the results of **NC** with respect to **HC**, that indicates the improvement of manipulation performance precision due to using haptic feedback.

2.5.2 Scenario 2: opening a door

In the second experiment, a building after an earthquake was simulated that was close to collapse. A quadrotor similar to the previous simulation study is used to open the door of the building. The quadrotor was commanded in the body frame, such that the haptic device z -axis motion commanded the quadrotor in z -direction, and the x -axis motion of the haptic device was used to command the vehicle in x -direction in the body-frame, and y -axis motion of haptic device was used to specify the robot's desired angular velocity around z -axis of the body-frame. The mission was to open the door and then go inside the building and land on a landmark (Fig. 2.18). The subjects could always see the video stream of the quadrotor on-board cameras, and could also see the scene from a fixed point of view outside the building (they could see the quadrotor and building from outside of the building, but when quadrotor was inside they were not able to see the quadrotor anymore). Ten subjects (seven men, three women, aged 24-51) participated voluntarily, none of them never served in USAR teams, and they had no previous experience of working with UAVs and haptic devices. They performed the experiments after receiving enough explanation about the mission and training to learn how to drive the robot.

A typical result of the experiment is depicted in Fig.2.14 to Fig.2.18. Position tracking performance is shown in Fig.2.14 that shows the position commands ($\mathbf{p}_p$, and $\mathbf{p}_f$), and the performance of position tracking ($\mathbf{p}_d$ vs $\mathbf{p}$). As can be seen from the figures, position tracking results shows a high performance of the system in tracking position commands. Fig.2.15 shows the orientation commands and performance of the system in tracking the desired orientation. The desired yaw that is need to keep the quadrotor tool perpendicular to the door is depicted by ψ_f , and this signal is automatically generated by the PI-controller that regulates the force along the y -direction. Fig.2.16 shows the desirable performance of system in tracking the force commands, as can be seen from the picture there is only a single jumping from the surface of the door in the docking phase. The force along z -axis during the interaction phase is not controlled, because controlling the normal force such that the quadrotor tool stay perpendicular to the door was the concern of experiment. The low frequency force oscillations that are visible in the figure are due to using high gain PI-controller for force tracking in order to not lose the contact while interacting with the moving object. This vibrations do not affect the objective of the controller for this particular case, which is pushing the door to open it, as the vibrations are around a positive force value far from zero. Fig.2.17 illustrates the different components of the haptic feedback during the experiment. The first component $\mathbf{f}_{pD}$ is shown at the top, while the second component of the force haptic feedback, $\mathbf{f}_{pf}$, that is composed by $(1 - u(\mathbf{f}_e))S_p^b \mathbf{e}_p$ and $S_f^b \mathbf{f}_e$ are shown in the second and third sub-figures, respectively. As it is obvious the second and last components of the force are complement of each other, when in contact the second component is zero, and when in free flight the third component is zero. And finally, Fig.2.18 shows the door angle during the simulation time. Notice that high angular friction and weight of the door, and low power of the quadrotor caused a slow, smooth, and almost linear motion. Studying the results of

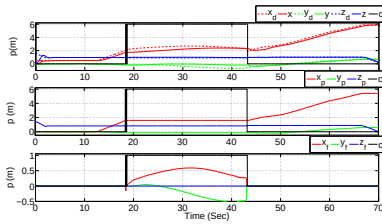


Figure 2.14: Position commands and performance in the second human/hardware in the loop experiments (pushing a door to open it).

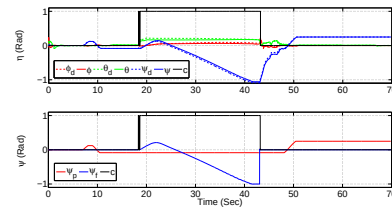


Figure 2.15: Orientation commands and performance in the experiment of pushing a door to open it.

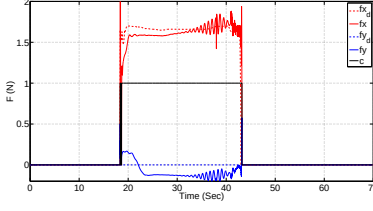


Figure 2.16: Force commands and performance in the experiment of pushing a door to open it.

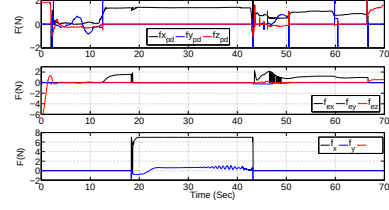


Figure 2.17: Different components of haptic feedback in the experiment of pushing a door to open it.

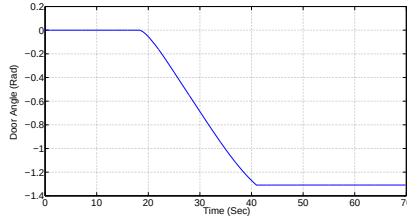


Figure 2.18: The door angle in the experiment of pushing a door to open it.

the users in performing the experiment with and without haptic feedback revealed the following important result:

- ◇ All the users completed the experiment in sufficiently short time of training and short time of experiment. Thus we may conclude the ease of use for the system in practical situations.
- ◇ The mean and standard deviation of time to complete the task for with and without haptic feedback conditions were 59.2170 ± 11.2941 s and 61.5140 ± 9.9811 s, respectively. These results indicate about 4% increase in flight time, that compare to the current short endurance of small size aerial robots is practically significant.
- ◇ The mean and standard deviation of the force tracking performance index that is defined as $(I_F = \frac{\int_0^{t_f} |f_{d,x} - f_x| dt}{t_f})$ for with and without haptic feedback conditions were 0.2442 ± 0.0166 N and 0.3006 ± 0.0190 N. A paired-samples t-test was used to determine whether this 20% difference in force tracking performance is statistically significant or not. There was no outliers in the collected data. The assumption of normality was not violated, as assessed by Shapiro-Wilk's test ($p =$

0.963). The paired-samples t-test results ($t(9) = 2.185$, $p = .057$, $d = 0.69$) revealed that difference in force tracking improvement by having force feedback (for this particular task) is not significant.

2.6 Conclusions

In this chapter, we have presented a control scheme to let a human operator drive a quadrotor, equipped with a light weight passive tool, in a remote environment. The proposed unified control scheme allows to control the position of the robot in free flight and the force applied to the environment during contact interaction. For this purpose, a parallel position/force controller is utilized. The desired position of the quadrotor, during the free flight, is given by master device position integration, that allows to control the position of the vehicle in an unlimited workspace using a limited workspace haptic device. Once a contact is established, the position of the end-effector (where the contact is established) is kept and additional movement of the master device is interpreted as desired force to be applied to the object. The force is controlled using an outer PI loop that provides the inner position controller with additional position command to achieve the desired force. In order to avoid losing the contact, the desired force commanded by the human operator is checked to satisfy the friction constraint of the contact. If the commanded force is outside the friction cone, the robot is asked to follow a modified force vector, which is obtained by projection on the surface of the friction cone. The human operator is provided with force haptic feedback proportional to the position tracking error in free flight and applied force in contact. Experiments on driving toward a desired point, docking and applying desired forces to fix and moving objects represented the feasibility of using lightweight passive tool to apply desired force vectors and the efficiency of parallel position/force controller in position and force tracking. Two user studies, based on human/hardware in the loop simulations, have shown the ease of use, and importance of haptic feedback in improving the performance of users in object manipulation in the remote virtual environment.

Cooperative Aerial Tele-Manipulation with Haptic Feedback

3.1 Introduction

In this chapter, we propose to the best of our knowledge the first bilateral tele-operation scheme for cooperative aerial manipulation in which a human operator drives a team of MRARs (as, *e.g.*, quadrotors), that grasped an object beforehand, and receives a haptic feedback depending on the system's states, *i.e.*, inertia of the object, and repulsive force to avoid obstacles. For application scenarios in which dexterous manipulation performed by a single UAV is not necessary, we propose using a rigid tool equipped with a simple gripping mechanism at the tool-tip that can stick to the grasped object as, *e.g.*, a simple 1-DoF gripper, and attached to the MRAR CoM through a passive spherical joint. In fact, using a spherical joint at the CoM of the MRAR makes the fast rotational dynamics of the MRARs decoupled from the slow dynamics of the grasped object [56]. From the point of view of the object dynamics, for more than two MRARs we obtain a redundant system. These extra degrees of freedom in determining the forces applied by each MRAR is used to satisfy the constraints of the system. For each MRAR, in order to produce the desired 3D force, an appropriate total thrust and desired orientation is obtained.

The MRAR's passive tools need to be connected to the manipulated object. There are several possible approaches to realize it, such as the gripping mechanisms proposed in [90, 91]. When the manipulated object is ferromagnetic, one can use small flat permanent magnets; this mechanism is common in wall climbing robot [92], and also is used for quadrotors. Using vacuum suction cups is another option, such as the perching mechanism used for quadrotor in [93]. New technologies such as magnetorheological fluids [94], micro-structured adhesives [95], or dry adhesion materials, which have been exploited in climbing robots [96], and quadrotors [97, 98] can also be considered as a good solution to produce a considerable amount of connecting force. Throughout the chapter, we assume that one of these approaches is used, and we refer to the force produced by one of these methods at the contact points as the *adhesive forces*. We then explicitly take

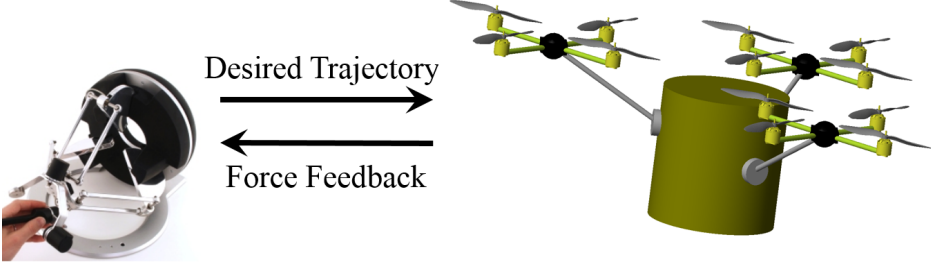


Figure 3.1: Schematic representation of the proposed bilateral teleoperation for cooperative aerial manipulation.

into account the constraints imposed by the maintenance of the adhesive force.

The rest of the chapter is organized as follows. Section 3.2 explains the dynamic model of the system. Section 3.3 describes the control system architecture. Human/Hardware-in-the-loop simulation results in which a human operator drives a MRAR team, consisting of three quadrotors carrying an object, via a multi-DoF haptic device is presented in Section 3.4, the experimental result of bilateral aerial tele-manipulation is presented in 3.5, and the concluding remarks are outlined in Section 3.6.

This Chapter is a revised version of the work published as [99].

3.2 System Model

The teleoperation scheme consists of a haptic device (master), a team of n MRAR aerial robots, having physical constraints, attached to the object (slave), and a communication channel between them.

3.2.1 Slave Model

In order to derive the dynamic model of the system let us define the world frame $\mathcal{W} : \{O_{\mathcal{W}}, w_1, w_2, w_3\}$, the object frame $\mathcal{B}_o : \{O_B^o, b_1^o, b_2^o, b_3^o\}$, the body frames $\mathcal{B}_i : \{O_B^i, b_1^i, b_2^i, b_3^i\}$ for each robot $i = 1 \dots n$, and the contact frame $\mathcal{C}_i : \{O_c^i, o_i, t_i, n_i\}$ for each contact point $i = 1 \dots n$, placed where the adhesive mechanism of each passive tool is attached to the grasped object. The points O_B^o and $O_B^i, i = 1 \dots n$, coincide with the CoMs of the object and the robots, respectively. The normal vectors n_i in the contact frames point to the out of the object (Fig. 3.2).

The position of O_B^i in $\mathcal{W}$ is indicated with $p_i = [p_1^i \ p_2^i \ p_3^i]^\top \in \mathbb{R}^3$, and $m_i \in \mathbb{R}^+$ and $J_i \in \mathbb{R}^{3 \times 3}$ are the mass and inertia matrix of each robot, respectively. The

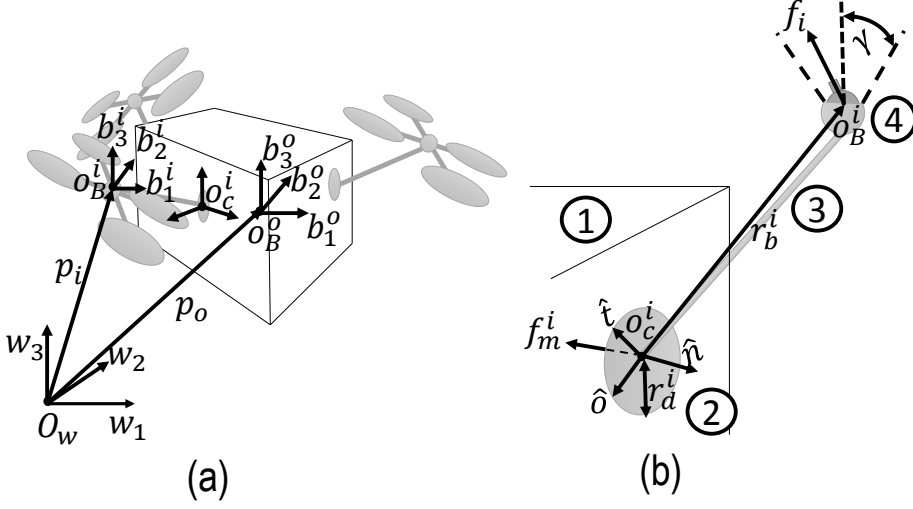


Figure 3.2: (a, b) Coordinate frames for a team of quadrotors manipulating an object. (b) Passive tool mechanism: an adhesive disc (2) attached to the grasped object (1) and connected to the spherical joint (4) through a lightweight bar (3).

orthogonal matrix $R_i \in SO(3)$ represents the rotation from $\mathcal{W}$ to $\mathcal{B}_i$. We consider the RPY parametrization of R_i , i.e., $\boldsymbol{\eta}_i := [\phi_i \ \theta_i \ \psi_i]^\top \in \mathbb{R}^3$, where ϕ, θ, ψ are the roll, pitch and yaw angles, respectively. The angular velocity of $\mathcal{B}_i$ with respect to $\mathcal{W}$, expressed in $\mathcal{B}_i$, is denoted with $\boldsymbol{\omega}_i \in \mathbb{R}^3$.

The magnitude of the total thrust acting along the $\mathbf{b}_3^i$ direction, denoted with $\lambda_i \in \mathbb{R}^+$, and the total moment expressed in $\mathcal{B}_i$, denoted with $\mathbf{u}_i = [u_1^i \ u_2^i \ u_3^i]^\top$, are the four control inputs of each robot. The i -th MRAR's dynamic equation of motion in the operational space is

$$M_i(\mathbf{x}_i)\ddot{\mathbf{x}}_i + \mathbf{b}_i(\mathbf{x}_i, \dot{\mathbf{x}}_i) + \mathbf{g}_i = \mathbf{h}_i + \mathbf{l}_i \quad (3.1)$$

where $\mathbf{x}_i = [\mathbf{p}_i^\top \ \boldsymbol{\eta}_i^\top]^\top \in \mathbb{R}^6$ is the robot pose, $\dot{\mathbf{x}}_i$ and $\ddot{\mathbf{x}}_i$ are its velocity and acceleration. The matrix $M_i \in \mathbb{R}^{6 \times 6}$ is the inertia matrix, and is defined as follows

$$M_i = \begin{bmatrix} m_i I_{3 \times 3} & 0_{3 \times 3} \\ 0_{3 \times 3} & M_{\boldsymbol{\eta}, i}(\boldsymbol{\eta}_i) \end{bmatrix}$$

where $M_{\boldsymbol{\eta}, i}(\boldsymbol{\eta}_i) = E_i^\top J_i E_i \in \mathbb{R}^{3 \times 3}$. The vector $\mathbf{b}_i = [0_{1 \times 3} \ (C_i(\boldsymbol{\eta}_i, \dot{\boldsymbol{\eta}}_i)\dot{\boldsymbol{\eta}}_i)^\top]^\top$ is the Coriolis/centripetal effect, where $C_{\boldsymbol{\eta}, i}(\boldsymbol{\eta}_i, \dot{\boldsymbol{\eta}}_i) = E_i^\top J_i \dot{E}_i + E_i^\top S(E_i \dot{\boldsymbol{\eta}}_i) J_i E_i \in$

$\mathbb{R}^{3 \times 3}$, and $E_i(\boldsymbol{\eta}_i) \in \mathbb{R}^{3 \times 3}$ is a matrix that relates $\boldsymbol{\omega}_i$ to $\dot{\boldsymbol{\eta}}_i$ as $\boldsymbol{\omega}_i = E_i(\boldsymbol{\eta}_i)\dot{\boldsymbol{\eta}}_i$, and $S(\mathbf{a})$ denotes the skew-symmetric matrix corresponding to a generic vector $\mathbf{a}$. The vector $\mathbf{g}_i = [(m_i g \mathbf{w}_3)^\top \mathbf{0}_{1 \times 3}]^\top \in \mathbb{R}^6$ is the gravity vector in which g is the gravity acceleration constant.

The control input vector of each MRAR, expressed in $\mathcal{W}$, is $\mathbf{h}_i = [\mathbf{f}_i^\top \boldsymbol{\tau}_i^\top]^\top \in \mathbb{R}^6$, where $\mathbf{f}_i = \lambda_i R_i [0 \ 0 \ 1]^\top \in \mathbb{R}^3$ and $\boldsymbol{\tau}_i = E_i^\top \mathbf{u}_i \in \mathbb{R}^3$. The load effect of the carried object on each MRAR is expressed by $\mathbf{l}_i = [\mathbf{d}_i^\top \mathbf{0}_{1 \times 3}]^\top \in \mathbb{R}^6$. Note that using the spherical joint at the CoM of the MRAR, we can assume the forces from the object result in negligible torques on the CoM of the MRAR, and we can consider the orientation of each MRAR independent from the orientation of the object [56], a part from the presence of spherical joint limits that will be carefully considered in our control framework.

Let $m_o \in \mathbb{R}$ and $\mathbf{J}_o \in \mathbb{R}^{3 \times 3}$ be the mass and inertia matrix of the object, and matrix $R_o \in \mathbb{R}^{3 \times 3}$ represent the rotation matrix from $\mathcal{W}$ to $\mathcal{B}_o$. The dynamic equation of motion for the object carried by the team of MRARs is

$$M_o(\mathbf{x})\ddot{\mathbf{x}} + \mathbf{b}_o(\mathbf{x}, \dot{\mathbf{x}}) + \mathbf{g}_o = -G\mathbf{d} \quad (3.2)$$

where $\mathbf{x} = [\mathbf{p}_o^\top \boldsymbol{\eta}_o^\top]^\top$ is the object's CoM pose, $M_o(\mathbf{x}) \in \mathbb{R}^{6 \times 6}$ and $\mathbf{b}_o(\mathbf{x}, \dot{\mathbf{x}}) \in \mathbb{R}^6$ are the inertial matrix and Coriolis/centripetal term, $\mathbf{g}_o(\mathbf{x})$ is the gravity vector, $\mathbf{d} = [\mathbf{d}_1^\top \dots \mathbf{d}_n^\top]^\top \in \mathbb{R}^{3n}$ is a vector containing forces applied by all the MRARs to the object, and $G = [G_1 \dots G_n] \in \mathbb{R}^{6 \times 3n}$ is the grasp matrix in which each G_i is

$$G_i = \begin{bmatrix} \mathbf{I}_{3 \times 3} & S(R_o^\top \mathbf{r}_i)^\top \end{bmatrix}^\top \quad (3.3)$$

where $\mathbf{r}_i \in \mathbb{R}^3$ is a vector describing the point of application of the total thrust of the i -th MRAR, *i.e.*, the fixed distance of O_B^i , the CoM of each MRAR, from O_B^o , the CoM of the object, in $\mathcal{B}_o$. Therefore, notice that the point included in the grasp matrix is the CoM of the i -th MRARs rather than the contact point O_c^i (where the adhesive mechanism of the passive tool is attached to the transported object). The position of O_B^i , in $\mathcal{W}$, as depicted in Fig. 3.2 (a) is

$$\mathbf{p}_i = \mathbf{p}_o + R_o \mathbf{r}_i. \quad (3.4)$$

The force applied to the object by the i -th robot, *i.e.*, $\mathbf{d}_i$, is the opposite of the first 3 components of $\mathbf{l}_i$ in (3.1), and can be written as

$$\mathbf{d}_i = m_i(\ddot{\mathbf{p}}_o + \ddot{R}_o \mathbf{r}_i + g \mathbf{w}_3) - \mathbf{f}_i. \quad (3.5)$$

Substituting (3.5) in (3.2), we may express the whole system dynamic equation of motion as follows.

$$M(\mathbf{x})\ddot{\mathbf{x}} + \mathbf{b}(\mathbf{x}, \dot{\mathbf{x}}) + \mathbf{g} = G\mathbf{f} \quad (3.6)$$

where $M(\mathbf{x}) \in \mathbb{R}^{6 \times 6}$, $\mathbf{b}(\mathbf{x}, \dot{\mathbf{x}}) \in \mathbb{R}^6$, and $\mathbf{g} \in \mathbb{R}^6$ are the inertial matrix, Coriolis/centripetal term, and gravity vector; $\mathbf{f} = [\mathbf{f}_1^\top \dots \mathbf{f}_n^\top]^\top \in \mathbb{R}^{3n}$ is a vector containing total thrust (control) forces of all robots. Equation (3.6) has the form of the augmented object model, which is well-known in cooperative mobile manipulation literature [100], with the only difference that this time it has been derived for a team of underactuated aerial robots rather than for a team of mobile manipulators or a standard robotic hand.

In this chapter, we assume that a grasp planner arranges the contact points, such that the grasp matrix G is full row rank, *i.e.*, $\text{Rank}(G) = 6$. This is always true for more than two non-collinear contact points [17].

3.2.2 Master Model

The gravity compensated dynamic model of the haptic interface with n_m DoFs can be described as

$$M_m(\mathbf{x}_m)\ddot{\mathbf{x}}_m + C_m(\mathbf{x}_m, \dot{\mathbf{x}}_m)\dot{\mathbf{x}}_m = \mathbf{f}_h + \mathbf{f}_c \quad (3.7)$$

where $\mathbf{x}_m \in \mathbb{R}^{n_m}$ is the configuration vector of the interface, $M_m(\mathbf{x}_m) \in \mathbb{R}^{n_m \times n_m}$, is the inertia matrix, $C_m(\mathbf{x}_m, \dot{\mathbf{x}}_m) \in \mathbb{R}^{n_m \times n_m}$ is the Coriolis/centripetal matrix, and $\mathbf{f}_h \in \mathbb{R}^{n_m}$ and $\mathbf{f}_c \in \mathbb{R}^3$ are the human and control forces, respectively [101].

3.2.3 System Constraints

We consider the following constraints in our model:

- ◇ there are spherical joint limits, *i.e.*, the set of allowed rotation of the spherical joints is realistically limited,
- ◇ each MRAR has a limited thrust, *i.e.*, the total thrust magnitude for each MRAR must be comprised between a minimum and a maximum value (both positive),
- ◇ the object is fragile, *i.e.*, there is a maximum normal force applicable to the object at the contact point,
- ◇ bounded strength of the adhesion mechanism at the contact point, *i.e.*, the internal wrench at the contact point must be bounded in order to either keep the adhesion to the surface or to not break the gripper, depending on the contact method used.

3.3 Control System

In the proposed bilateral teleoperation control scheme for cooperative aerial manipulation, the desired object pose (position and orientation) is generated online by the human

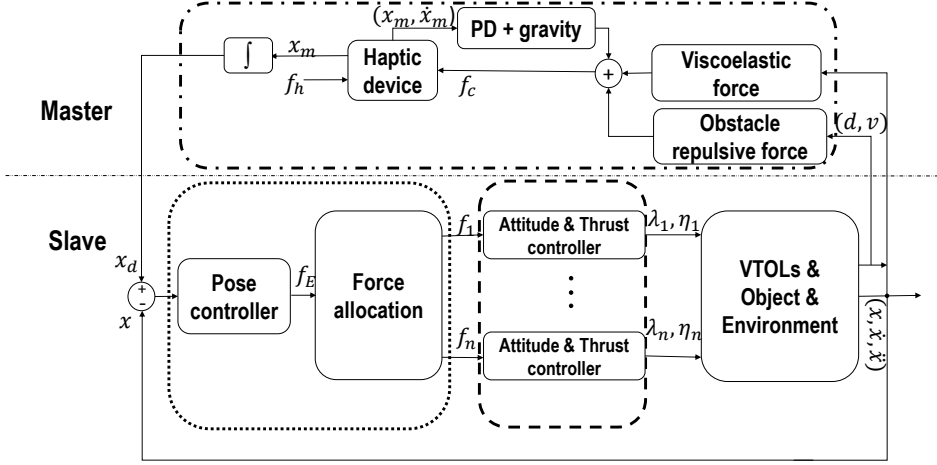


Figure 3.3: The bilateral teleoperation scheme for cooperative aerial manipulation: the object pose controller and force allocation algorithm (dotted rectangle), the MRARs' thrust-and-attitude controller (dashed rectangle), and the haptic feedback (dash-dotted rectangle).

operator through a haptic device. The desired object pose and the current state of the object are then sent to the *object pose controller* that computes the desired total wrench that, if perfectly executed by the team of MRARs, would let the object asymptotically track the desired object pose. The desired total wrench is then passed to the *force allocation* algorithm that, exploiting the system redundancy, computes a set of n desired forces to be applied at the n MRAR CoMs. The collective execution of these forces produces the desired total wrench and, at the same time, satisfies all the set of constraints, which have been introduced in Sec 3.2.3 and will be formally defined in Sec 3.3.2. Finally, the desired force corresponding to each MRAR is passed to the corresponding *attitude-and-thrust controller* (one for each MRAR) that controls the moment and thrust magnitude of the MRAR in order to track the desired force to be applied at the MRAR CoM. On the backward channel of the bilateral teleoperation scheme, the human receives a force feedback that depends on the inertia of the whole system and on a repulsive viscoelastic virtual force generated with the purpose of letting the operator feel the obstacles in the environment. In the following we explain in detail all the components of the control scheme which are summarized in Figure 3.3.

3.3.1 Object Pose Controller

The object pose controller generates a desired wrench $\mathbf{f}_E \in \mathbb{R}^6$ to balance the object dynamics, cancel possible external disturbances, and track the desired pose trajectory $\mathbf{x}_d \in \mathbb{R}^6$ commanded by the human operator. Let $\hat{M}$, $\hat{\mathbf{b}}$, and $\hat{\mathbf{g}}$ be the estimation of M , $\mathbf{b}$, and $\mathbf{g}$, respectively. The pose control law is defined as

$$\begin{cases} \mathbf{f}_E = \hat{M}(\mathbf{x})\boldsymbol{\mu} + \hat{\mathbf{b}}(\mathbf{x}, \dot{\mathbf{x}}) + \hat{\mathbf{g}}(\mathbf{x}) \\ \boldsymbol{\mu} = K_P \tilde{\mathbf{x}} + K_D \dot{\tilde{\mathbf{x}}} \end{cases} \quad (3.8)$$

where $\tilde{\mathbf{x}} = \mathbf{x}_d - \mathbf{x}$ is the pose error, and $K_P, K_D \in \mathbb{R}^{6 \times 6}$ are the diagonal control gain matrices with positive entries.

3.3.2 Force Allocation Algorithm

The force allocation algorithm exploits the redundancy of the system in order to generate the desired wrench and at the same time satisfy the system constraints which are formally derived in the following.

Let $[f_{i,b}^x \ f_{i,b}^y \ f_{i,b}^z]^\top = \lambda_i R_o^\top R_i [0 \ 0 \ 1]^\top \in \mathbb{R}$ be the force components produced by each MRAR at O_B^i , expressed in $\mathcal{B}_o$, and $\gamma \in (0, \frac{\pi}{2})$ be half of the aperture angle of the cone that defines the maximum rotation allowed by the spherical joint. The force components must comply with the following inequality

$$f_{i,b}^z \geq \vartheta \sqrt{(f_{i,b}^x)^2 + (f_{i,b}^y)^2}$$

where $\vartheta = \tan(\gamma) \in \mathbb{R}^+$ describes the possible cone of rotation. This constraint can be rewritten as

$$\|\mathbf{f}_i\| \leq \beta f_{i,b}^z \quad (3.9)$$

where $\beta = \frac{\sqrt{1+\vartheta^2}}{\vartheta} \in \mathbb{R}^+$.

The norm of each force vector, applied by each MRAR to the spherical joint, must comply with the actuators allowed range.

$$f_p^{min} \leq \|\mathbf{f}_i\| \leq f_p^{max} \quad (3.10)$$

where $f_p^{max} \in \mathbb{R}^+$ is the upper bound specified by the motors power, and $f_p^{min} \in \mathbb{R}^+$ is the lower bound, demanded by the motors to stay operational.

To avoid damaging the object, the component of the force along $-\mathbf{n}_i$ must be less than a threshold

$$\mathbf{f}_i^\top \mathbf{n}_i \geq -f_m^n \quad (3.11)$$

where $f_m^n \in \mathbb{R}^+$ depends on the fragility of the object.

Now let $\mu_s, \mu_t \in \mathbb{R}^+$ be the linear and rotational static friction coefficients between the adhesive disk and the object surface. The adhesive contact force $\mathbf{f}_i^m$ can be expressed as

$$\mathbf{f}_i^m = -k_i^m \mathbf{n}_i$$

where $k_i^m \in \mathbb{R}^+$ is a constant related to the strength of the adhesion mechanism. We indicate with $\boldsymbol{\tau}_c^i = S(\mathbf{r}_b^i) \mathbf{f}_i$ the torques applied to the adhesive disc of radius $r_d^i \in \mathbb{R}^+$, expressed in contact frame, as $\boldsymbol{\tau}_c^i = [\tau_o^i, \tau_t^i, \tau_n^i]^\top$. Where $\mathbf{r}_b^i$ is vector showing the fixed distance of each robot's CoM, that is, the spherical joint place, from the contact point, which is the center of the adhesive disk (Fig. 3.2 (b)). To avoid breaking the contact, the normal force component magnitude applied at each contact point must be less than the adhesive force magnitude. Furthermore, the total normal force at each contact point is the sum of the adhesive force and the normal component of the force applied by each MRAR. Thus, in each contact point to avoid planner slippage, the magnitude of linear static friction force must be greater than the magnitude of the planar force, and to avoid rotational slippage, the magnitude of the rotational friction torque must be greater than the magnitude of the normal torque component (τ_n^i). Moreover, to avoid breaking the contact due to other two torque components (τ_o^i and τ_t^i), the sum of their magnitudes must not be greater than the adhesive torque magnitude (the adhesive force result) around any pivot point at the disk edge. The constraints on forces and torques to avoid breaking the contact are summarized as

$$\begin{cases} \sqrt{(\mathbf{f}_i^\top \mathbf{t}_i)^2 + (\mathbf{f}_i^\top \mathbf{o}_i)^2} \leq \mu_s |k_i^m + (\mathbf{f}_i^\top \mathbf{n}_i)| \\ \mathbf{f}_i^\top \mathbf{n}_i \leq k_i^m \\ \|\boldsymbol{\tau}_i^n\| \leq \mu_t |k_i^m + (\mathbf{f}_i^\top \mathbf{n}_i)| \\ \sqrt{(\boldsymbol{\tau}_i^t)^2 + (\boldsymbol{\tau}_i^o)^2} \leq r_d^i k_i^m \end{cases} \quad (3.12)$$

The constraints (3.9), (3.10), (3.11), and (3.12) for all MRARs can be summarized as $\chi(\mathbf{f}) = [\chi_1^\top(\mathbf{f}_1) \dots \chi_n^\top(\mathbf{f}_n)]^\top \leq 0$, where $\chi_i(\mathbf{f}_i) : \mathbb{R}^3 \rightarrow \mathbb{R}^8$ is defined as follows

$$\chi_i(\mathbf{f}_i) = \begin{bmatrix} \|\mathbf{f}_i\| - \beta f_{i,b}^z \\ \|\mathbf{f}_i\| - f_p^{max} \\ -\|\mathbf{f}_i\| + f_p^{min} \\ -\mathbf{f}_i^\top \mathbf{n}_i - f_m^n \\ \sqrt{(\mathbf{f}_i^\top \mathbf{t}_i)^2 + (\mathbf{f}_i^\top \mathbf{o}_i)^2} - \mu_s |k_i^m + (\mathbf{f}_i^\top \mathbf{n}_i)| \\ \mathbf{f}_i^\top \mathbf{n}_i - k_i^m \\ \|\boldsymbol{\tau}_i^n\| - \mu_t |k_i^m + (\mathbf{f}_i^\top \mathbf{n}_i)| \\ \sqrt{(\boldsymbol{\tau}_i^t)^2 + (\boldsymbol{\tau}_i^o)^2} - r_d^i k_i^m \end{bmatrix}. \quad (3.13)$$

The problem of force allocation, is also subject to the equality constraints $\xi(\mathbf{f}) = 0$

where $\xi : \mathbb{R}^{3n} \rightarrow \mathbb{R}^6$ is

$$\xi(\mathbf{f}) = G\mathbf{f} - \mathbf{f}_E \quad (3.14)$$

The force allocation problem can be seen as a programming problem to minimize the cost function

$$J(\mathbf{f}) = \frac{1}{2} \mathbf{f}^\top \mathbf{f} + \varepsilon (\mathbf{f} - \mathbf{f}_{k-1})^\top (\mathbf{f} - \mathbf{f}_{k-1}) \quad (3.15)$$

where $J : \mathbb{R}^{3n} \rightarrow \mathbb{R}$, and $\mathbf{f} \in \mathcal{F}$, where $\mathcal{F}$ is the feasible solution set defined by the inequality and equality constraints (3.13) and (3.14). The solution of the optimization problem in the previous time step is denoted with $\mathbf{f}_{k-1}$, and $\varepsilon \in \mathbb{R}$ is a positive scalar. The convex quadratic cost function (3.15) is a weighted sum of a minimal force objective and a term penalizing variation. ε is a tuning knob directly proportional to the input smoothness, as that non negative term is minimized if $\mathbf{f} = \mathbf{f}_{k-1}$. In summary, the force allocation problem is

$$\begin{aligned} \mathbf{f}^* = \arg \min_{\mathbf{f}} \quad & J(\mathbf{f}) \\ \text{s.t.} \quad & \chi(\mathbf{f}) \leq 0 \\ & \xi(\mathbf{f}) = 0. \end{aligned} \quad (3.16)$$

Both $\chi(\mathbf{f})$ and $\xi(\mathbf{f})$ are affine functions of the optimization variable $\mathbf{f}$. That, along with $J(\mathbf{f})$ being convex quadratic, makes (3.16) a convex quadratic programming problem. There are several standard efficient methods to solve this problem, see, e.g., [102]. In (3.16), $J(\mathbf{f})$, $\chi(\mathbf{f})$, $\xi(\mathbf{f})$ are all twice continuously differentiable with respect to $\mathbf{f}$. By exploiting pre-computed first and second derivative of the cost function and constraints, the solver saves a considerable amount of online time [103].

3.3.3 Attitude-and-Thrust Controller

The attitude-and-thrust controller generates the thrust and moment controls of the MRAR corresponding to the allocated desired force $\mathbf{f}_i$ of each MRAR. For each MRAR, the thrust magnitude is directly controlled, and the yaw angle is set to follow the object yaw angle. As previously stated in Section 3.2.1 $\mathbf{f}_i = \lambda_i R_i [0 \ 0 \ 1]^\top$, thus the desired thrust $\lambda_d^i \in \mathbb{R}^+$ and the desired rotation matrix $R_d^i \in SO(3)$ can be defined as

$$\begin{cases} \lambda_d^i = \mathbf{f}_i^\top R_i [0 \ 0 \ 1]^\top \\ \frac{\mathbf{f}_i}{\|\mathbf{f}_i\|} = R_d^i [0 \ 0 \ 1]^\top. \end{cases} \quad (3.17)$$

A wide range of attitude controllers, such as the one presented in [26] can be used to produce τ_i . Let us define the orientation matrix error as

$$\mathbf{e}_R^i = \frac{1}{2} S^-(R_d^{i\top} R_i - R_i^\top R_d^i) \quad (3.18)$$

where $S^-(\bullet)$ is the inverse operation of $S(\bullet)$, the rotation error, corresponding to the rotation matrix $R_d^\top R$, is

$$e_\omega^i = \omega_i - R_i^\top R_d^i \omega_d^i \quad (3.19)$$

where $\omega_d^i \in \mathbb{R}^3$ is the desired angular velocity, and the attitude control law τ_i is

$$\tau_i = -K_R e_R^i - K_\omega e_\omega^i + \omega_i \times J_i \omega_i \quad (3.20)$$

in which $K_R, K_\omega \in \mathbb{R}^{3 \times 3}$ are diagonal matrices with positive elements. Interested readers are encouraged to see [26] for the stability proof of the controller.

3.3.4 Haptic feedback

The human operator changes the master robot position x_m by applying f_h to it. In order to cope with the limited workspace of the haptic device, the integrated over time x_m is given to the slave as reference pose trajectory x_d . The control force for the master device f_c is computed as

$$f_c = f_m + f_o + f_e. \quad (3.21)$$

The term f_m , which is intended to bring back the haptic probe to its centered position in order to avoid drifting of the slave, is defined as

$$f_m = -K_h \text{sat}(x_m, x_m^{max}) - B_h \dot{x}_m \quad (3.22)$$

where $K_h, B_h \in \mathbb{R}^{3 \times 3}$ are diagonal gain matrices with positive entries, $x_m^{max} \in \mathbb{R}^+$ is a scalar to limit the force, $\text{sat}(x_m, x_m^{max})$ is a saturation function defined as

$$\text{sat}(x_m, x_m^{max}) = \begin{cases} x_m & \text{if } \|x_m\| \leq x_m^{max} \\ \frac{x_m}{\|x_m\|} x_m^{max} & \text{otherwise} \end{cases} \quad (3.23)$$

The first term in the rhs of (3.22) is to set the haptic probe in absence of external forces. The second term is a damping factor that prevents oscillatory behaviors of the device.

The repulsive force feedback f_o is meant to avoid collision with the obstacles in the environment and is based on the basic risk field (BRF) [70]

$$f_o = \begin{cases} 0 & \text{if } \frac{1+v}{d_{res}(d,v)} \leq 0 \\ f_o^{max} n_o & \text{if } \begin{cases} d_{res}(d,v) \leq 0 \\ \frac{1+v}{d_{res}(d,v)} \geq \frac{1}{k_o} \end{cases} \\ k_o \frac{1+v}{d_{res}(d,v)} n_o & \text{otherwise} \end{cases}, \quad (3.24)$$

where $\mathbf{n}_o \in \mathbb{R}^3$ is the unit vector representing the direction of the repulsive force, d is distance from the obstacle, v is the component of velocity toward the obstacle, k_o is a gain to tune the sensitivity, f_o^{max} is the maximum force to be felt in haptic device, and the reserve avoidance distance d_{res} is defined as

$$d_{res}(d, v) = \begin{cases} \frac{2a_{max}d+v^2}{2a_{max}} & \text{if } v \leq 0 \\ \frac{2a_{max}d-v^2}{2a_{max}} & \text{if } v > 0 \end{cases}, \quad (3.25)$$

where a_{max} is the maximum deceleration in the obstacle direction.

Finally, the term $\mathbf{f}_e$ in (3.22) is intended to improve the tracking performance

$$\mathbf{f}_e = K_1 \tilde{\mathbf{x}} + K_2 \dot{\tilde{\mathbf{x}}}, \quad (3.26)$$

where $\tilde{\mathbf{x}} = \mathbf{x}_d - \mathbf{x}$, $\dot{\tilde{\mathbf{x}}} = \dot{\mathbf{x}}_d - \dot{\mathbf{x}}$, and $K_1, K_2 \in \mathbb{R}^{3 \times 3}$ are diagonal matrices with positive elements.

3.4 Human/Hardware in the Loop Simulations

Human/Hardware In the Loop (HIL) simulations have been performed in Simulink® using SimMechanics™ with a control loop of 1 ms for haptic interface, 10 ms for quadrotors thrust and attitude controller, and the force allocation optimization solver.

In order to solve the optimization problem we adopted the open source tool Optpp [104] and in particular an instance of OptNIPS problem, namely an implementation of Newton nonlinear interior-point method with analytic Hessian information. Pre-computed analytic representations of the first and second derivatives of the cost function and constraints were obtained by means of Matlab® symbolic and code generation toolboxes, which produced C++ code eventually bound to Simulink® via a C++ level-2 S-Function.

The HIL simulation scenario is as follows. The MRAR team consists of three quadrotors carrying a barrel in the virtual environment, and a human operator drives them via a 3-DoF actuated haptic device (Fig. 3.4). The initial position of the grasped object is $(0, 0, 0)$, while the ground is considered a flat surface 1 meter below the object, and the target point is $(-7 \text{ m}, 0, 0)$. There is a cube shape obstacle of size $(3 \text{ m}, 6 \text{ m}, 3 \text{ m})$ centered at $(-2 \text{ m}, 0, 0)$. The mission is complete when the object's CoM is closer than 25 cm to the target point (Fig. 3.5). The translation of the haptic device is integrated to generate the reference trajectory for the object and the desired orientation set to be zero. The weight of each quadrotor, including the adhesive mechanism, is 0.7 kg, and the

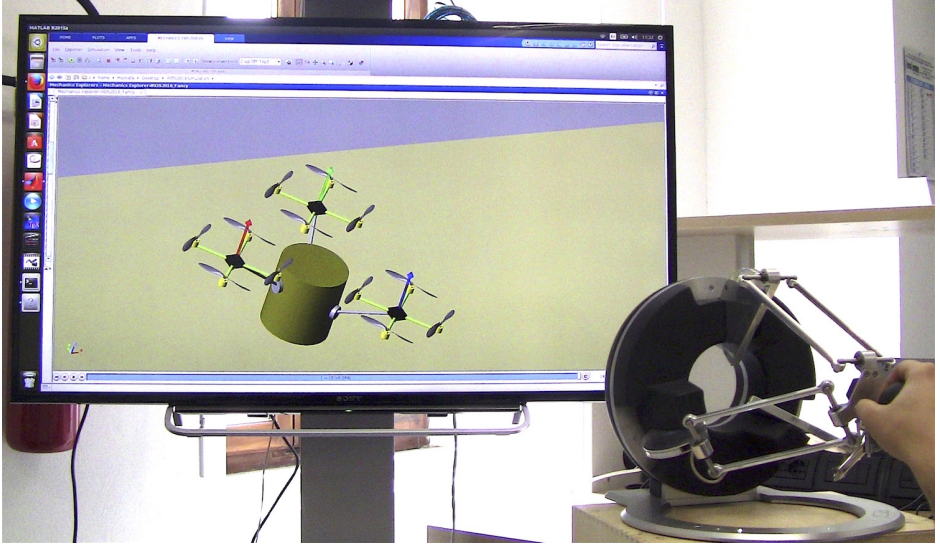


Figure 3.4: HIL simulation setup.

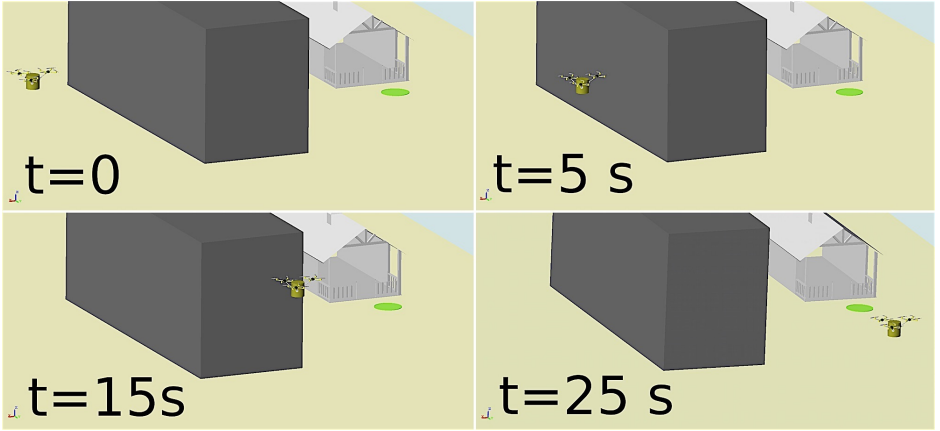


Figure 3.5: HIL simulation scenario.

object is cylinder of 30 cm height, 12 cm radius and 2.4 kg weight. Locating the contact points exactly in the desired positions, which are determined by a grasp planner, is very difficult in our problem. Thus, we considered up to 10% uncertainty (with respect to the object size) in locating the contact points. Table 3.1 and Table 3.2 show the gain matrices

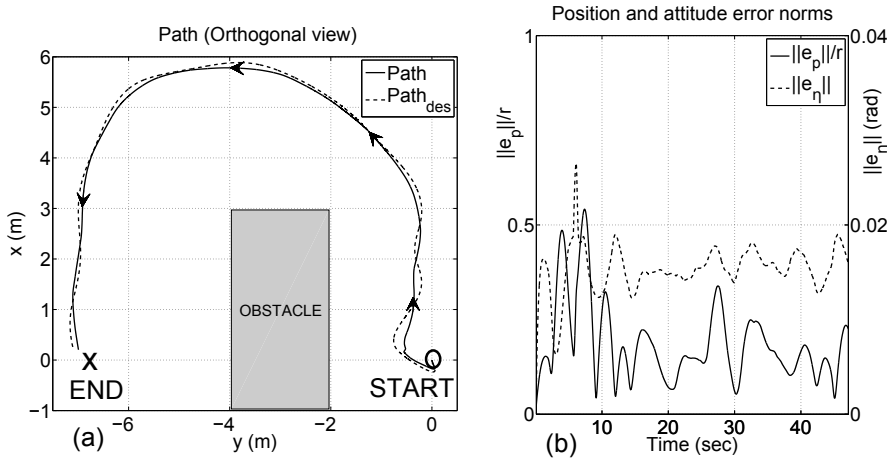


Figure 3.6: (a) Desired and actual path of the MRAR team carrying the object. The path shows the orthogonal view of the object's CoM. (b) Euclidean norm of the position error (left y -axis), which is normalized by the radius size of the team. Euclidean norm of the attitude error (right y -axis).

and constraints of the system used in the HIL simulation study.

A typical HIL simulation results are presented in Fig. 3.6, 3.7, 3.8, 3.9 in which the subject completed the task in 47.5 seconds. Fig. 3.6(a) shows the commanded trajectory by the human operator and the actual path of the MRAR team carrying the object from the orthogonal view (xy -plane). Fig. 3.6(b) represents the normalized Euclidean norm of the position error (left y -axis) and attitude error (right y -axis). The position error norm is normalized by the team radius r , *i.e.*, the circumambient sphere radius, to show the control system efficiency. It is evident that the position error norm is smaller than half of the r , where $r = 60$ cm. And the small error of the attitude norm is due to the uncertainty in the grasp matrix. Fig. 3.7(a,b) depicts the object pose controller output (f_E) to follow the user commanded trajectory, where the force elements are shown in Fig. 3.7(a) and the torque elements in Fig. 3.7(b). The force allocation algorithm generates the desired vector forces of each quadrotor, that is shown in Fig. 3.7(c, d, e). To generate the force allocated to each quadrotor, attitude and thrust controller controls the attitude of quadrotors Fig. 3.8(a, c, e). Then, the thrust of four motors are calculated and applied to the motors to achieve the desired attitude and thrust Fig. 3.8(b, d, f). As it can be seen, due to the appropriate controller gains, the thrust of the motors are reasonable

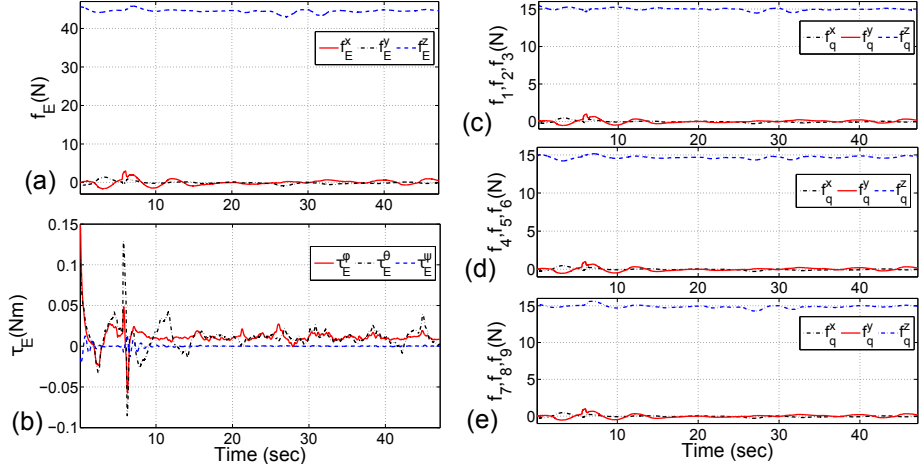


Figure 3.7: (a) Object pose controller output forces (the first three elements of f_E). (b) Object pose controller output torques (the last three elements of f_E). (c, d, e) The allocated force vectors to the three quadrotors.

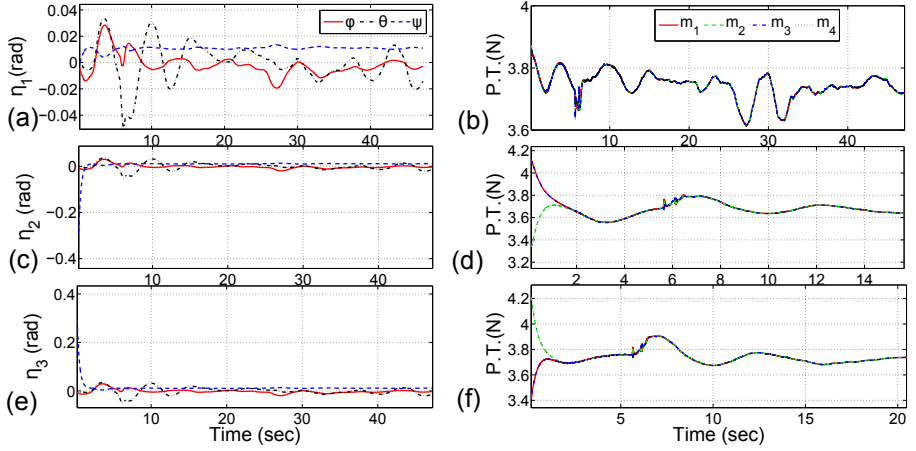


Figure 3.8: (a, c, e) The attitude of MRARs to produce their own allocated force vectors. (b, d, f) The thrust of four motors for each quadrotor to achieve the desired thrust and the attitude.

both in value and rate. At the master side, the position of the haptic probe (x_m) is shown in Fig. 3.9(b), and the corresponding force (f_m), which is keeping the haptic probe at the center to avoid vehicle drifting, due to the integral action, which is intended to cope with

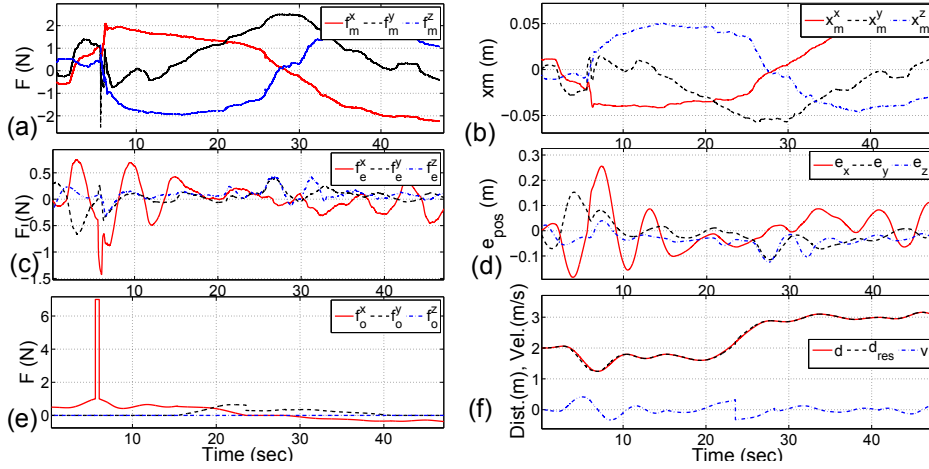


Figure 3.9: (a) Centering force at the master side (f_m), (b) the position of the haptic probe (x_m). (c) Force feedback to improve the tracking performance (f_e). (d) Position error in trajectory tracking. (e) The repulsive force feedback (f_o). (e) Distance (d), reserve avoidance distance (d_{res}), and the velocity (v) towards the obstacle.

the limited workspace of the haptic device, is shown in Fig. 3.9(b). The force feedback to improve the tracking performance (f_e) in correspondence to the position error in tracking the desired trajectory is shown in Fig. 3.9(c), and the position error in 3.9(d) represents the high performance of the tele-operated system with the maximum position error less than 30 cm during the flight time. The repulsive force feedback (f_o) to avoid the obstacle is shown in Fig. 3.9(e), which is calculated according to the distance (d), reserve avoidance distance (d_{res}), and the velocity (v) towards the obstacle Fig. 3.9(f).

In order to study the haptic feedback effect, we asked 10 subjects to do the HIL experiment once with haptic feedback and once without haptic feedback. The subject were able to see the virtual environment from a single fixed camera in the environment, thus did not have a full view of the MRARs, due to the existence of the big obstacle in the environment. Using haptic feedback, 10% of the subjects experienced failure by colliding the object, while without haptic feedback 20% of the subjects had the incomplete task, due to the collision with the obstacle. For 10 successful trials, the time to complete the task (t_f) is shorter with haptic feedback than without it, and also the tracking performance (in term of $\frac{1}{t_f} \int_0^{t_f} \|\hat{x}\| dt$) is smaller for trials with haptic feedback than without haptic feedback. The average and standard deviation of the time to complete the task and

Table 3.1: Gain matrices used in the HIL simulation study. All the values are presented in SI.

Description	Symbol	Value
Pose controller proportional gain	K_P	$diag\{2, 2, 5, 1, 1, 1\}$
Pose controller derivative gain	K_D	$diag\{5, 5, 5, 3, 3, 3\}$
MRAR attitude proportional gain	K_R	$diag\{2, 2, 2\}$
MRAR attitude derivative gain	K_ω	$diag\{0.5, 0.5, 0.5\}$
Haptic feedback proportional gain (centering force)	K_h	$diag\{50, 50, 50\}$
Haptic feedback derivative gain (centering force)	B_h	$diag\{1, 1, 1\}$
Haptic feedback gain (pose error proportional)	K_1	$diag\{0.5, 0.5, 0.5\}$
Haptic feedback gain (pose error derivative)	K_2	$diag\{0.5, 0.5, 0.5\}$
Haptic feedback repulsive gain	k_o	1
Haptic feedback maximum repulsive force	f_o^{max}	7
Maximum deceleration of the MRAR team	a_{max}	1

Table 3.2: The system Constraints in HIL simulation study. All the values are presented in SI.

Description	Symbol	Value
Spherical joint's half angle of the rotation cone	γ	$\frac{\pi}{3}$
Maximum total thrust of each MRAR	f_p^{max}	40
Minimum total thrust of each MRAR	f_p^{min}	4
Fragility coefficient of the object	f_n^m	100
Adhesive contact force coefficient	k_i^m	30
Linear friction coefficient	μ_s	1
Angular friction coefficient	μ_t	1
Adhesive disk radius	r_d	0.05

Table 3.3: Time to complete the task and tracking performance in HIL simulation study for ten subjects.

	With haptic feedback	Without haptic feedback
Time to complete the task (<i>Avg.</i>)	26.88 sec	27.82 sec
Time to complete the task (<i>Std.</i>)	5.21 sec	3.92 sec
Tracking performance (<i>Avg.</i>)	0.134 m	0.172 m
Tracking performance (<i>Std.</i>)	0.038 m	0.038 m

tracking performance are summarized in Table 3.3.

3.5 Experimental Results

Preliminary experiments have been performed to validate the proposed control scheme for bilateral cooperative aerial tele-manipulation. The same quadrotor and software setup of the previous chapter has been used for the experiments. The quadrotor is equipped with a lightweight tool, that all its rotational degrees of freedom (spherical joint) are locked during the free flight (Fig. 3.10 (top)). The adhesive mechanism, that is three magnets in the Fig. 3.10 (bottom-left), (later has been replaced with Velcro that has a better functionality), and a micro-switch that is triggered by contacting, i.e., once the tool attached to the manipulated object, the lock and release mechanism (Fig. 3.10 (bottom-right)), that composed by a small fork-like arm (the black object) that is attached to the shaft of a DC-servo motor, and the servo motor is commanded by the micro-switch. If micro-switch is off, i.e., not in contact, the fork-like arm hold the tool arm firmly, and once the micro-switch is triggered the servo motor rotates and the fork-like arm will not be around the tool arm anymore, and the tool arm will be released. The master device used for the proof of concept experiment is an Omega.7 haptic device that has three active translational degrees of freedom, three passive rotational degrees of freedom and active gripper. The human operator commands the desired pose of the object by moving the haptic device (Fig. 3.11 (left)). A team of MRARs composed of two quadrotors equipped with the above mentioned lightweight tools are used to grasp the object and move it around (Fig. 3.11 (right)). Aerial transportation of a grasped object by an MRAR team composed of two quadrotors in an environment consists of obstacles is the scenario of the experiment (Fig. 3.12). The object is a cuboid of size $0.45\text{ m} \times 0.45\text{ m} \times 0.15\text{ m}$ and as heavy as 0.5 kg (half of the weight of each quadrotor). The contact points are located at the center of two big side of the cuboid. The grasp matrix for the configuration used for the experiment has rank 5, thus we control only 5 degrees of freedom of the object, namely three dimensional degrees of freedom and pitch and yaw. In this preliminary experiment, the optimization problem is eliminated and force allocation has been performed by simply finding the pseudo-inverse of the grasp matrix, regardless of internal forces, we allocated the force vector to each MRAR such that the object tracks the desired commanded force. This was made possible thanks to using Velcro as strong adhesive mechanism. Note that in this experiment the object desired yaw is set to be the initial object yaw, the quadrotors yaw are set such that the tool be perpendicular to the object.

The scene includes an obstacle in the center and all the walls around are also con-

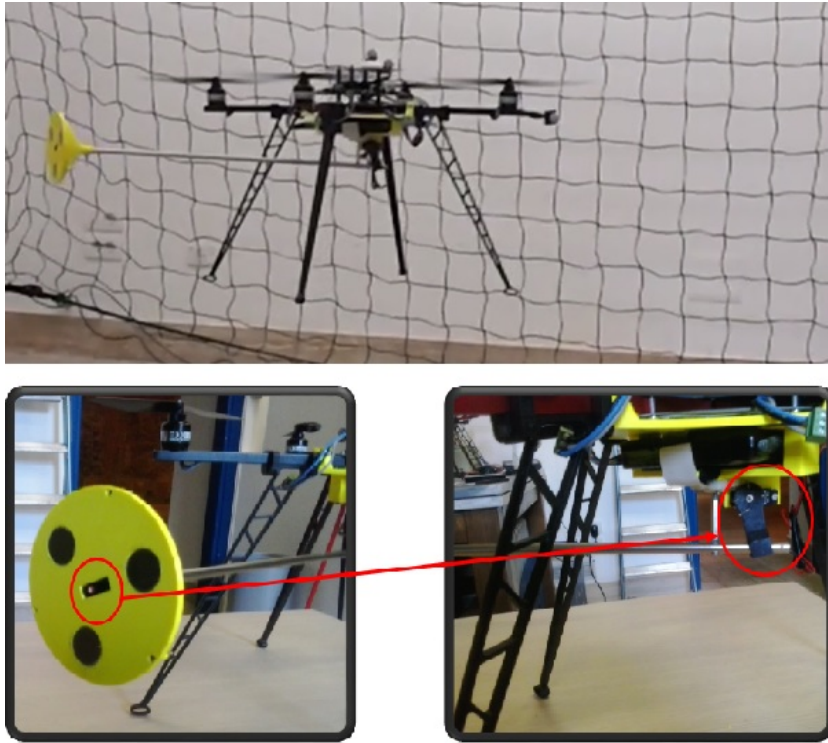


Figure 3.10: (top) The quadrotor equipped with a lightweight tool (bottom-left) The adhesive mechanism and a micro-switch, (bottom-right) the lock and release mechanism, that composed by a fork-like small arm (the black object) that is attached to the shaft of DC-servo motor.

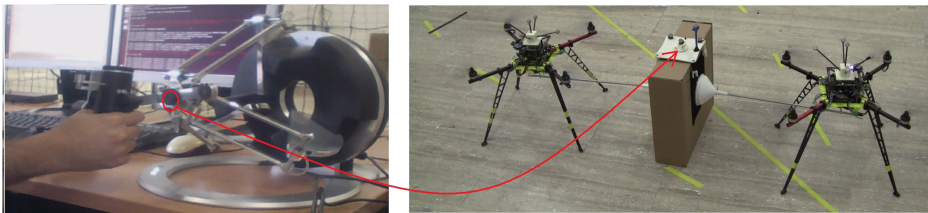


Figure 3.11: (right) The master device by which the human operator commands the desired pose of the object, (left) A team of MRARs composed of two quadrotors equipped with lightweight tools that grasped the object. Adhesive mechanism is Velcro in this picture.

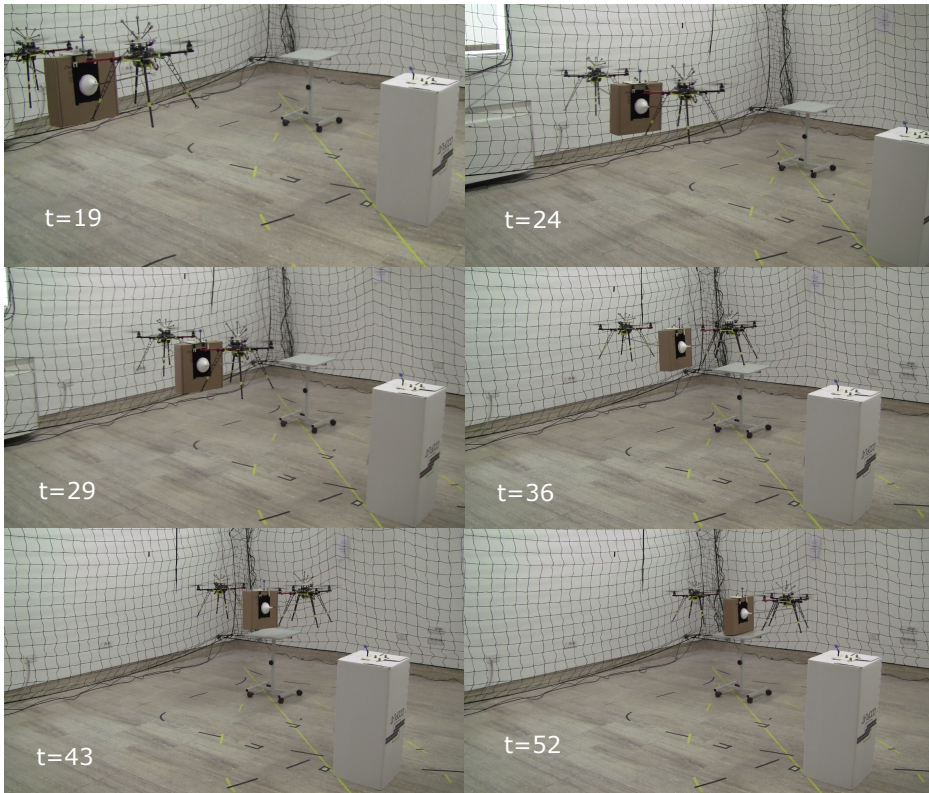


Figure 3.12: Snapshots of the experiment (aerial transportation of the grasped object by MRAR team). The scene includes an obstacle in the center and all the walls around are also considered as obstacles.

sidered as obstacles, the human operator wants to put the grasped object on the table at the corner of the flying arena (Fig. 3.12). The obstacle in the center prevents the user from connecting the initial and final point using a straight line, thus a complicated path is demanded, and considering the small space of the flying arena ($5\text{ m} \times 5\text{ m} \times 3\text{ m}$) and relatively big size the MRAR team that grasped the object ($1.5\text{ m} \times 0.5\text{ m} \times 0.5\text{ m}$) a precise position tracking is demanded. Moreover the limited view of the human operator make the use of haptic feedback for obstacle avoidance necessary. Fig. 3.13-3.17 show the result of the experiment. Fig. 3.13 shows the pose tracking performance of the system, and Fig. 3.14 shows the path of the object in space and plane. This result illustrated an

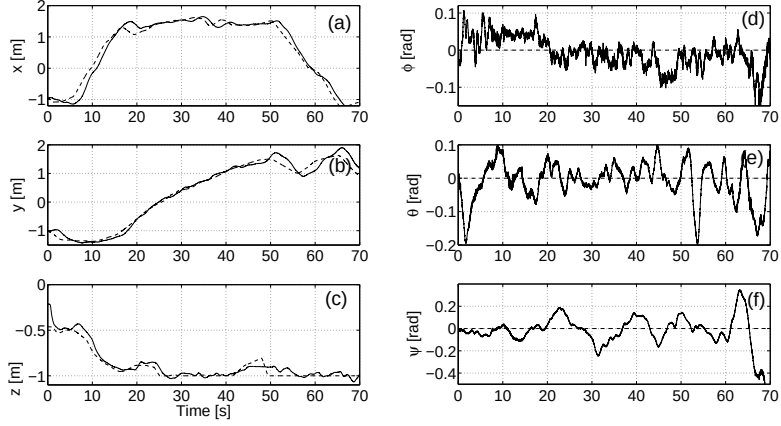


Figure 3.13: (a, b, c) The desired (commanded by human operator) and actual position of the object during the experiment. (d, e, f) The desired and actual attitude of the object during the experiment.

acceptable system performance in position tracking that practically validates the proposed control scheme and shows that the proposed mechanical solution for the lightweight tool is efficient enough. Fig. 3.15 (a) and (d) show the allocated force to each quadrotor during the experiment, and Fig. 3.15 (b) and (e) and Fig. 3.15 (c) and (f) show the attitude and thrust of each vehicle, respectively, that has been calculated using the attitude and thrust controller. Fig. 3.16 shows the haptic feedback signal related to position error, which has intended to improve the position tracking performance.

Fig. 3.17 shows the haptic feedback signal related to obstacle avoidance for the obstacle in the center, note that for the sake of clarity, the signals related to the flying arena border (that has been considered as obstacles) are not shown in this figure. The haptic feedback plays an essential role to help the human user to drive the robot team safely in the cluttered environment. Fig. 3.17 shows the haptic feedback (in force form) that displayed by the haptic device to the user. Note that the obstacle avoidance haptic force feedback in z -direction is deactivated.

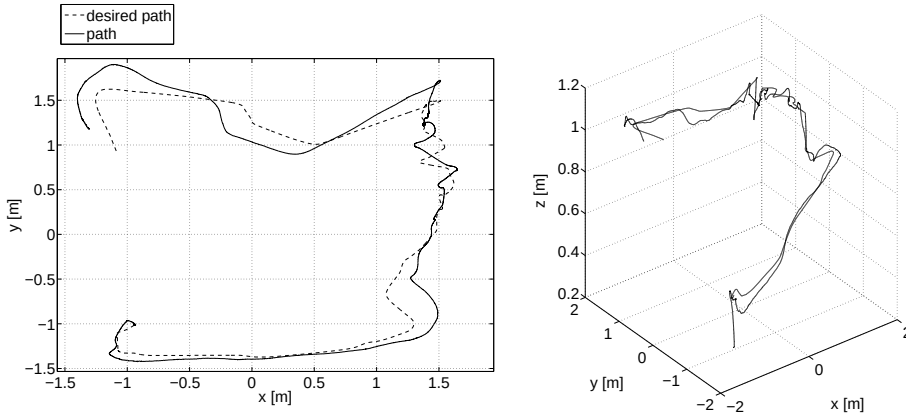


Figure 3.14: (right) The desired and actual path of the object in the horizontal plane. (left) The desired and actual path of the object in three dimensional space.

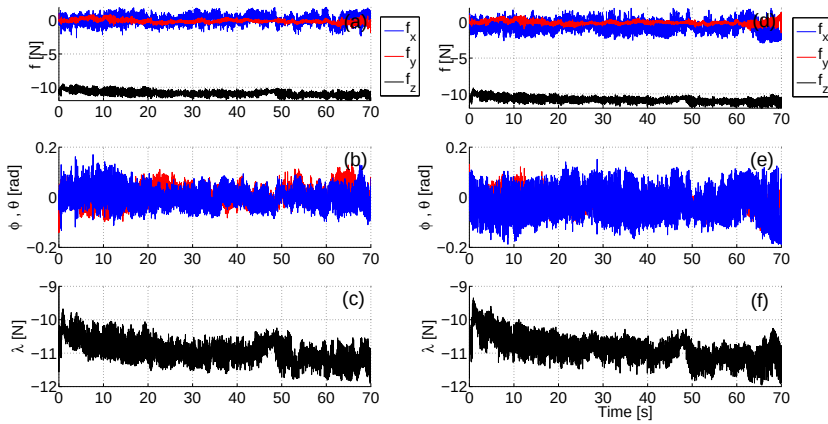


Figure 3.15: a) and (d) the allocated force to each quadrotor during the experiment, (b) and (e) the attitude and (c) and (f) thrust of each vehicle.

3.6 Conclusion

In this chapter a bilateral tele-operation scheme for cooperative aerial manipulation is presented. A human operator drives a team of MRARs holding an object, which is

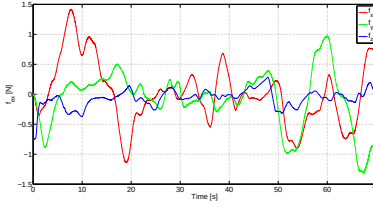


Figure 3.16: Haptic feedback signal related to position error, which has intended to improve the position tracking performance.

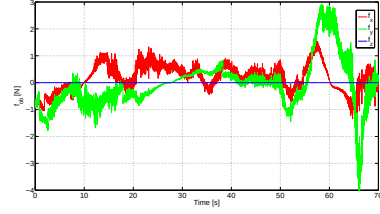


Figure 3.17: The haptic feedback related to the obstacle avoidance.

grasped in advance, receives a force feedback based on the system state, *i.e.*, position tracking error, repulsive force to avoid obstacles. To simplify mechanical design, each UAV equipped with a passive adhesive tool connected via spherical joint to the vehicle. The granted redundancy, in case of more than two robots, is used to optimally allocate among team members, the forces to track object pose reference. The on-line quadratic programming problem solves the allocation trading between force magnitude and signal smoothness, while enforcing system constraints. An attitude and thrust controller regulates the motor thrusts and attitude of each vehicle to meet the desired allocated force. A Human/Hardware in the loop simulation study showed the efficiency of the proposed scheme and the importance of haptic feedback in reducing the time to complete the task and also enhancing the tracking performance. Implementation with real robots, showed a very promising results that validates the mechanism and proposed control scheme.

Multiple Aerial-Ground Manipulating Systems

4.1 Introduction

In this chapter in order to overcome the payload issue we use a robotic (mobile) manipulators, that has a considerably higher payload compared to small MRARs, and this comes with no cost on the endurance side. The assistance provided by an MRAR or a fleet of them complements the natural imperfection of grounded robotic manipulators in dealing with large objects, and also expands their workspace.

Consider for example a robotic manipulator tasked to let a large object track a planned trajectory. This task can become unfeasible for some kind of objects or objects/trajectories combination, e.g., with long objects requiring a lot of torque for horizontal pick-up, or precise manipulation of long objects grasped at one end, or for flexible objects. More specifically consider the task of inserting a long bar into the ceiling, to do that a manipulator will typically need assistance in two parts of the task. First for lifting the bar held by one of its extremity, as even a lightweight bar generates considerable torques when rotated at one of its end. Assistance will also be needed to precisely position the bar into a hole in the ceiling, as a small angular displacement at the grasping point will result in a large motion at the other end. In these and many other situations, such as Urban Search And Rescue (USAR) scenarios, see Fig. 4.1, an aerial manipulator, or a fleet of them can improve the precision of the tracking task, and ensure multiple contacts thus allowing to neglect the object flexibility. We use the term ‘MAGMaS’ (Multiple Aerial-Ground Manipulator System) to refer to these kind of multi-robot systems. To the best of our knowledge, this work presents the first complete analysis, control, and redundancy exploitation for a multi-robot team of the MAGMaS type.

Our contribution is twofold: first we derive the model of a robotic system composed of a manipulator and a fleet of aerial robots. Then we propose a nonlinear control scheme, that considers existing uncertainties of the model and system constraints, and optimizes the *Force Manipulability Index* for trajectory tracking tasks. The proposed approach is finally validated through realistic numerical simulations and a preliminary real-world



Figure 4.1: Representation of a MAGMaS, a heterogeneous multi-robot system composed by a ground manipulator and one aerial robot, in a USAR scenario. Overlaid are the main coordinate frames, states, and control inputs used in the dynamic modeling.

experiment.

MAGMaS might be used in either fully autonomous system, teleoperated, or shared control manner. In this chapter we present the system as an autonomous system, in order to focus on characteristic properties of the robotic team on the remote side. The extension to bilateral teleoperation approach is straightforward by adapting the teleoperation scheme of Chapter 3. Teleoperation and shared control approach of MAGMaS, that we call it Tele-MAGMaS, is a practical approach to tackle applications in unstructured environment such as search and rescue and logistics, while the autonomous system might be used in construction and assembly.

The rest of the chapter is organized as follows, Sec. 4.2 presents the system dynamic model, and Sec. 4.3 explains the controller design. Numerical simulations are then presented in Sec. 4.4 and preliminary experimental results in Sec. 4.5. Finally, in Sec. 4.6 we comment our results and give a future perspective.

This Chapter is a revised version of the work published as [?].

4.2 Problem Formulation

We consider a heterogeneous multi-robot system composed by an n -DoFs *manipulator*, and k MRARs. The task of the system is to cooperatively manipulate an *object*, $\mathcal{O}$. In the following we describe the notation and derive a model of the system, which is

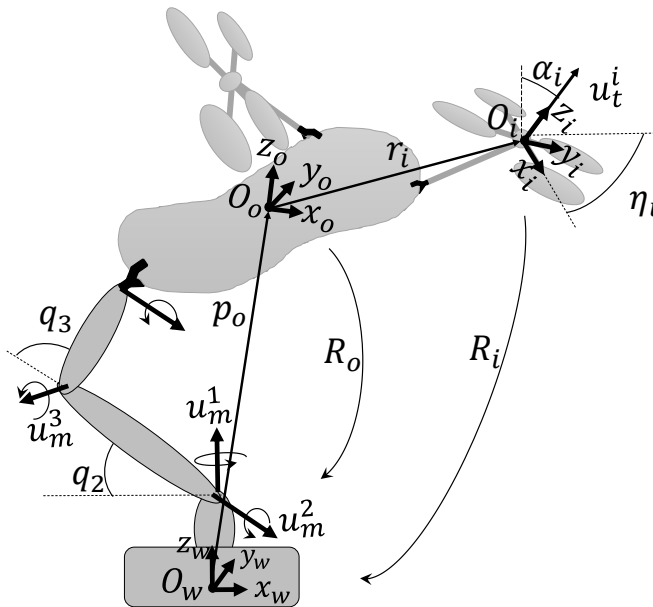


Figure 4.2: Representation of a MAGMaS multi-robot team, a heterogeneous multi-robot system composed by a ground manipulator and several aerial vehicles. The main coordinate frames, states, and control inputs used in the dynamic modeling are depicted too.

schematically depicted in Fig. 4.2. Each UAV is equipped with a *grasping link* that is attached to its CoM by means of a passive spherical joint. At the other end, the grasping link is equipped with a gripper that is used to rigidly grasp the object. Each grasping link has a braking system that can be either turned-on or turned-off. In turned on condition the link is fixed with respect to MRAR body, i.e., the spherical joint is locked, and in the other condition the spherical joint is released and can rotate passively. In a first phase the braking systems of each grasping link are turned on and the aerial robots, together with the manipulator, grasp the object in some different points. In the second phase, once the approaching and grasping are completed, the braking systems of the grasping links are turned off and the manipulator and aerial robots have to control the motion of $\mathcal{O}$ in a cooperative way, exploiting their redundancy and heterogeneity. In this chapter we focus only on this second phase, i.e., on the cooperative manipulation as such.

4.2.1 Dynamic Model

First, consider a world frame $\mathcal{W} : \{O_{\mathcal{W}}, \mathbf{x}_w, \mathbf{y}_w, \mathbf{z}_w\}$, an object body frame $\mathcal{O} : \{O_{\mathcal{O}}, \mathbf{x}_o, \mathbf{y}_o, \mathbf{z}_o\}$, with $O_{\mathcal{O}}$ being the CoM of the manipulated object, and without loss of generality let us assume that this coordinate frame is parallel to the arm end-effector frame. Then set a body frame $\mathcal{O}_i : \{O_i, \mathbf{x}_i, \mathbf{y}_i, \mathbf{z}_i\}$ for each MRAR, with O_i being the CoM of the i -th UAV and $i \in \{1 \dots k\}$ as depicted in Fig. 4.2.

Let us denote with $\mathbf{p}_o \in \mathbb{R}^3$, and $\mathbf{R}_o \in SO(3)$ the position of $O_{\mathcal{O}}$ and the orientation of $\mathcal{O}$ w.r.t. $\mathcal{W}$, and with $\mathbf{p}_i \in \mathbb{R}^3$, and $\mathbf{R}_i \in SO(3)$ the position and orientation of $\mathcal{O}_i$ w.r.t. $\mathcal{W}$, respectively. The orientation of $\mathcal{O}_i$ and $\mathcal{O}$ with respect to $\mathcal{W}$ are described by set of angles $\boldsymbol{\eta}_i = [\phi_i \ \theta_i \ \psi_i]^\top \in \mathbb{R}^3$ and $\boldsymbol{\eta}_o = [\phi_o \ \theta_o \ \psi_o]^\top \in \mathbb{R}^3$, respectively, where ϕ_i, θ_i and ψ_i , are the roll, pitch, and yaw angle, respectively. The angular velocity of the object and the i -th MRAR w.r.t. $\mathcal{W}$ expressed in the corresponding body frame are denoted with $\boldsymbol{\omega}_o$ and $\boldsymbol{\omega}_i$, respectively. Furthermore, let $m_i \in \mathbb{R}^+$ and $\mathbf{J}_i \in \mathbb{R}^{3 \times 3}$ be the mass and inertia matrix of the i -th MRAR.

The i -th aerial robot exerts a thrust force $\mathbf{u}_t^i = u_t^i \mathbf{z}_i$ applied at its CoM with a controllable magnitude u_t^i and a direction $\mathbf{z}_i$ that is specified by the MRAR orientation, which is regulated by the control torque vector $\mathbf{u}_r^i = [u_x^i \ u_y^i \ u_z^i]^\top \in \mathbb{R}^3$. The dynamic equation of motion for each MRAR is as follows:

$$m\ddot{\mathbf{p}}_i + m_i g \mathbf{z}_w = u_t^i \mathbf{R}_i \mathbf{z}_b^i - \mathbf{h}_i \quad (4.1)$$

$$\mathbf{J}_i \dot{\boldsymbol{\omega}}_i + \boldsymbol{\omega}_i \times \mathbf{J}_i \boldsymbol{\omega}_i = \mathbf{u}_r^i \quad (4.2)$$

where $\mathbf{h}_i \in \mathbb{R}^3$ is the load of the system on i -th MRAR. From (4.2), recalling the relationship between $\boldsymbol{\omega}_i$, and the derivate of its Euler angles $\dot{\boldsymbol{\eta}}_i$ as $\boldsymbol{\omega}_i = \mathbf{E}_i(\boldsymbol{\eta}_i) \dot{\boldsymbol{\eta}}_i$, where the elements $\mathbf{E}_i(\boldsymbol{\eta}_i) \in \mathbb{R}^{3 \times 3}$ are trigonometric functions of $\boldsymbol{\eta}_i$, we can express the rotational dynamics of the i -th MRAR as follows:

$$\mathbf{M}_i \ddot{\boldsymbol{\eta}}_i + \mathbf{c}_i(\boldsymbol{\eta}_i, \dot{\boldsymbol{\eta}}_i) = \mathbf{u}_r^i \quad (4.3)$$

in which $\mathbf{M}_i = \mathbf{J}_i \mathbf{E}_i \in \mathbb{R}^{3 \times 3}$ is the rotational part of the inertia matrix of the i -th aerial robot, $\mathbf{c}_i(\boldsymbol{\eta}_i, \dot{\boldsymbol{\eta}}_i) = \left(\mathbf{J}_i \dot{\mathbf{E}}_i + \mathbf{S}(\mathbf{E}_i \dot{\boldsymbol{\eta}}_i) \mathbf{J}_i \mathbf{E}_i \right) \dot{\boldsymbol{\eta}}_i \in \mathbb{R}^3$ is the Coriolis/centripetal effect, and $\mathbf{S}(\mathbf{a})$ denotes the skew-symmetric matrix corresponding to a generic vector $\mathbf{a}$. The position of O_i in $\mathcal{O}$ is denoted by a constant vector $\mathbf{r}_i \in \mathbb{R}^3$. Thus we have $\mathbf{p}_i = \mathbf{p}_o + \mathbf{R}_o \mathbf{r}_i$ for any $i \in \{1, \dots, k\}$. The orientation of the MRARs do not appear as the passive joints are assumed to have their centers of rotation coinciding with the respective CoMs.

Denoting the joint coordinates of the ground manipulator with $\mathbf{q}_m = [q_1 \dots q_n]^\top \in$

$\mathbb{R}^n$ the manipulator dynamical model can be expressed as:

$$\mathbf{M}_m(\mathbf{q}_m)\ddot{\mathbf{q}}_m + \mathbf{c}_m(\mathbf{q}_m, \dot{\mathbf{q}}_m) + \mathbf{g}_m(\mathbf{q}_m) = \mathbf{u}_m - \mathbf{J}_m^\top(\mathbf{q}_m)\mathbf{h}_o \quad (4.4)$$

where $\mathbf{h}_o \in \mathbb{R}^6$ is the wrench applied by the arm to the object and MRARs system, expressed in the end-effector frame, which by convention is parallel to the object frame $\mathcal{O}$, $\mathbf{M}_m(\mathbf{q}_m) \in \mathbb{R}^{n \times n}$ is the positive definite inertia matrix, $\mathbf{c}_m(\mathbf{q}_m, \dot{\mathbf{q}}_m) \in \mathbb{R}^n$ and $\mathbf{g}_m(\mathbf{q}_m) \in \mathbb{R}^n$ represent the centrifugal/Coriolis and gravity terms, respectively, $\mathbf{J}_m(\mathbf{q}_m) \in \mathbb{R}^{6 \times n}$ is the geometric Jacobian of the arm, and $\mathbf{u}_m = [u_m^1 \dots u_m^n]^\top \in \mathbb{R}^n$ gathers the n joint torques of the manipulator.

The dynamical model of the whole system can be written considering $\mathbf{q} = [\mathbf{q}_m^\top \mathbf{q}_a^\top]^\top \in \mathbb{R}^{n+3k}$, where $\mathbf{q}_a = [\boldsymbol{\eta}_1^\top \dots \boldsymbol{\eta}_k^\top]^\top \in \mathbb{R}^{3k}$ and $\mathbf{u} = [\mathbf{u}_m^\top \mathbf{u}_r^\top]^\top \in \mathbb{R}^{n+3k}$, where $\mathbf{u}_r = [\mathbf{u}_r^1 \dots \mathbf{u}_r^k]^\top \in \mathbb{R}^{3k}$. We then obtain:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{c}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) = \mathbf{u} - \mathbf{J}^\top(\mathbf{q})\mathbf{h}, \quad (4.5)$$

where $\mathbf{M}(\mathbf{q}) \in \mathbb{R}^{n+3k \times n+3k}$, $\mathbf{c}(\mathbf{q}, \dot{\mathbf{q}}) \in \mathbb{R}^{n+3k}$ and $\mathbf{g}(\mathbf{q}) \in \mathbb{R}^{n+3k}$ have the same meaning as before but this time for the whole system. The term $\mathbf{h} \in \mathbb{R}^{6+3k}$ is defined as $\mathbf{h} = [\mathbf{h}_o^\top \mathbf{h}_t^\top]^\top$, where $\mathbf{h}_t = [\mathbf{h}_1^\top \dots \mathbf{h}_k^\top]^\top$. The matrix $\mathbf{J} \in \mathbb{R}^{(6+3k) \times (n+3k)}$ is the Jacobian of the robot team. Given the partitioning of $\mathbf{q}$ and the physical interconnections of the different systems, the following structure holds

$$\begin{aligned} \mathbf{M}(\mathbf{q}) &= \text{diag}\{\mathbf{M}_m(\mathbf{q}_m), \mathbf{M}_1(\boldsymbol{\eta}_1), \dots, \mathbf{M}_k(\boldsymbol{\eta}_k)\} \\ \mathbf{c}(\mathbf{q}, \dot{\mathbf{q}}) &= [\mathbf{c}_m(\mathbf{q}_m, \dot{\mathbf{q}}_m) \ \mathbf{c}_1(\boldsymbol{\eta}_1, \dot{\boldsymbol{\eta}}_1) \cdots \mathbf{c}_k(\boldsymbol{\eta}_k, \dot{\boldsymbol{\eta}}_k)]^\top, \\ \mathbf{g} &= [\mathbf{g}_m(\mathbf{q}_m) \ \mathbf{0}_{3k \times 1}]^\top, \quad \mathbf{J} = \text{diag}\{\mathbf{J}_m(\mathbf{q}_m), \mathbf{0}_3, \dots, \mathbf{0}_3\} \end{aligned}$$

The structure of $\mathbf{J}$ arises from the fact that the passive joints efficiently decouple the MRARs rotational dynamics. The dynamic equation of motion for the rigid body object completes the dynamic model of the system

$$\mathbf{M}_o(\mathbf{x})\ddot{\mathbf{x}} + \mathbf{c}_o(\mathbf{x}, \dot{\mathbf{x}}) + \mathbf{g}_o(\mathbf{x}) = \mathbf{h}_e \quad (4.6)$$

where $\mathbf{x} = [\mathbf{p}_o^\top \boldsymbol{\eta}_o^\top]^\top \in \mathbb{R}^6$ is the object pose vector, $\mathbf{M}_o \in \mathbb{R}^6$, $\mathbf{c}_o \in \mathbb{R}^6$, and $\mathbf{g}_o \in \mathbb{R}^6$ are inertial matrix, Coriolis/centripetal, and gravity vectors, respectively, and $\mathbf{h}_e$, called external wrench, is the resultant force of the arm manipulator and all the MRARs that moves the object, and can be calculated as follows

$$\mathbf{h}_e = \mathbf{G}\mathbf{h} \quad (4.7)$$

where $\mathbf{G} \in \mathbb{R}^{6 \times (6+3k)}$ is the grasp matrix defined as

$$\mathbf{G} = \begin{bmatrix} \mathbf{T}_m & \mathbf{G}_t(\mathbf{q}) \end{bmatrix} \quad (4.8)$$

where $T_m \in \mathbb{R}^{6 \times 6}$ transforms $\mathbf{h}_o$ from the end-effector frame to the world frame, and $G_t(\mathbf{q}) \in \mathbb{R}^{6 \times 3k}$ describes the influence of the aerial robot thrust vectors on the object motion. It is straightforward to obtain them as follows:

$$T_m = \begin{bmatrix} \mathbf{R}_o^\top & \mathbf{0} \\ \mathbf{S}(\mathbf{R}_o^\top \mathbf{r}_e) & \mathbf{R}_o^\top \end{bmatrix} \quad (4.9)$$

$$G_t(\mathbf{q}) = \begin{bmatrix} \mathbf{I}_3 & \dots & \mathbf{I}_3 \\ \mathbf{S}(\mathbf{R}_o^\top \mathbf{r}_i) & \dots & \mathbf{S}(\mathbf{R}_o^\top \mathbf{r}_k) \end{bmatrix} \quad (4.10)$$

where $\mathbf{r}_e \in \mathbb{R}^3$ is the position of the end effector in $\mathcal{O}$. Equations (4.6) and (4.5) completely describe the dynamics of the system. Now consider (4.7), the grasp matrix G is full-row rank, thus for a given $\mathbf{h}_e$ the inverse of (4.7) can be written as follows.

$$\mathbf{h} = G^+ \mathbf{h}_e + V \mathbf{h}_n = \mathbf{h}_E + \mathbf{h}_I \quad (4.11)$$

where G^+ is a pseudo-inverse of G , V is a full-row rank matrix spanning the null-space of G , and $\mathbf{h}_n$ is an arbitrary vector of appropriate dimension that parameterizes the solution sets [17, ?]. Concatenated force vector $\mathbf{h}_E$ are forces that can result in motion, while $\mathbf{h}_I$ are known as internal forces, and their directions are such that they do not contribute in motion.

4.2.2 System Constraints

In order to perform the given task, the controller must compute the manipulator joint torques and force vector of each AR that comply with the system constraints, which are provided in the following:

- ◇ the set of allowed rotation of the spherical joints are limited. Let the force applied by the i -th MRAR to the object, expressed in $\mathcal{W}$, be $\mathbf{h}_i = [h_i^x, h_i^y, h_i^z]^\top$. Denoting with $\alpha_i \in \mathbb{R}^+$ the allowed cone angle of a spherical joint the constraint can be written as:

$$\chi_i(\boldsymbol{\eta}_i) = \sqrt{(h_i^x)^2 + (h_i^y)^2} - \tan(\alpha_i) h_i^z \leq 0 \quad (4.12)$$

for $i = 1, \dots, k$;

- ◇ the robot manipulator joints have limited rotation range,

$$q_i^{\min} \leq q_i \leq q_i^{\max} \quad i = 1, \dots, n \quad (4.13)$$

notations	description
$\boldsymbol{\eta}_o = [\phi_o \ \theta_o \ \psi_o]^\top$	orientation of the object $\mathcal{O}$
$\boldsymbol{\eta}_i = [\phi_i \ \theta_i \ \psi_i]^\top$	orientation of the i -th MRAR
$\mathbf{u}_t^i = u_t^i \mathbf{z}_i$	thrust vector of the i -th MRAR
$\mathbf{u}_r^i = [u_x^i \ u_y^i \ u_z^i]^\top$	input torque of the i -th MRAR
$\mathbf{q}_m$	joint positions of the manipulator
$\mathbf{J}_m(\mathbf{q}_m)$	geometric Jacobian of the manipulator
$\mathbf{u}_m = [u_m^1 \ \dots \ u_m^n]^\top$	manipulator input torques
$\mathbf{q}_a = [\boldsymbol{\eta}_1^\top \ \dots \ \boldsymbol{\eta}_k^\top]^\top$	all MRARs orientations
$\mathbf{q} = [\mathbf{q}_m^\top \ \mathbf{q}_a^\top]^\top$	coordinates of the system
$\mathbf{u}_r = [\mathbf{u}_r^1 \ \dots \ \mathbf{u}_r^k]^\top$	torque of all MRARs
$\mathbf{u} = [\mathbf{u}_m^\top \ \mathbf{u}_r^\top]^\top$	input torques of the MRARs and the manipulator
$\mathbf{h}_t = [\mathbf{h}_1^\top \ \dots \ \mathbf{h}_k^\top]^\top$	load of the system on each MRAR
$\mathbf{h}_o$	wrench applied by the manipulator to the system
$\mathbf{h} = [\mathbf{h}_o^\top \ \mathbf{h}_t^\top]^\top$	coupling wrenches in the system
$\mathbf{x} = \mathbf{f}(\mathbf{q})$	Cartesian coordinate of the object $\mathcal{O}$
$\mathbf{h}_e = \mathbf{G}\mathbf{h}$	resultant wrench of the arm manipulator and all the MRARs
$\mathbf{T}_m$	matrix transforming from end-effector frame to the world frame
$\mathbf{t} = \mathbf{f}(\mathbf{q}_m)$	task function
$\mathbf{J}_t$	Jacobian matrix of the task
$\mathbf{u}_J = [\mathbf{u}_m^\top \ \mathbf{h}_t^\top]^\top$	manipulator torque and MRARs forces
$\mathbf{u}_E$	feedback-linearization-based control signal

Table 4.1: Main notations used through the chapter.

where $q_i^{\min}, q_i^{\max} \in \mathbb{R}^+$ are scalar values representing the upper and lower joint bounds;

◇ the robot manipulator torques are limited,

$$u_m^{\min} \leq u_m^i \leq u_m^{\max} \quad i = 1, \dots, n, \quad (4.14)$$

where $u_m^{\min}, u_m^{\max} \in \mathbb{R}$ represent the upper and lower torque bounds for the manipulator.

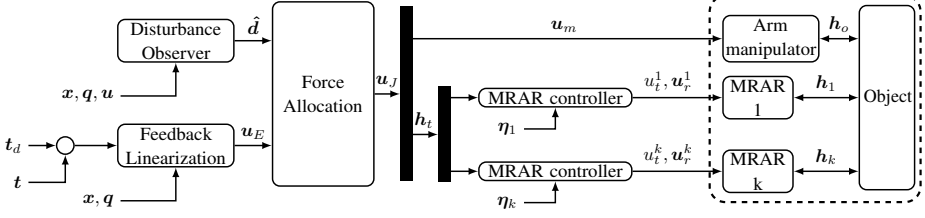


Figure 4.3: The proposed control scheme for MAGMaS (the dashed rectangle), is composed of a feedback linearization controller, a disturbance observer to deal with uncertainties, an optimization-based force allocation scheme and one AR force vector controllers for each aerial manipulator.

◇ each MRAR has a bounded thrust, i.e.,

$$\|h_i\| \leq h_i^{\max} \quad i = 1, \dots, k \quad (4.15)$$

where $h_i^{\max} \in \mathbb{R}^+$ is the maximum applicable thrust.

4.3 Control System

In this section the control architecture is detailed, feedback linearization is derived, the force allocation optimization problem is formalized and uncertainties handling is introduced. The overall control architecture is summarized in Fig. 4.3.

Consider a task associated to the manipulation of the object, such as trajectory tracking in operational workspace. The task is described by a set of variables $t \in \mathbb{R}^\sigma$. Since the object is a rigid body, whose pose is described by 6 coordinates, hence $\sigma \leq 6$. On the other hand, the object configuration only depends of the arm joint angles q_m , thus the task is function of the sole q_m ,

$$t = f(q_m). \quad (4.16)$$

where $f: \mathbb{R}^n \rightarrow \mathbb{R}^\sigma$ is a differentiable vector function assumed to be known for the given manipulator. A prerequisite for a generic reference to be trackable is that the map f is surjective, which, in turns, implies that $\sigma \leq n$. In conclusion, $\sigma \leq \min\{6, n\}$. Furthermore, we assume that the task is planned such as to comply with the limited rotation range of the robot manipulator joints, i.e. (4.13). The problem addressed in this work is to let the task t track a desired reference t_d while taking advantage of the MAGMaS redundancy and heterogeneity.

As control approach for the trajectory tracking task we use input-output exact linearization, via static feedback. Recall, in order to design a static feedback linearization

control law each output is differentiated until at least one input appears and the obtained differential map must result invertible. In our case, the first differentiation of the task w.r.t. time yields

$$\dot{\mathbf{t}} = \frac{\partial \mathbf{f}}{\partial \mathbf{q}_m} \dot{\mathbf{q}}_m = \mathbf{J}_t(\mathbf{q}_m) \dot{\mathbf{q}}_m = [\mathbf{J}_t(\mathbf{q}_m) \mathbf{0}_{\sigma_t \times 3k}] \dot{\mathbf{q}} \quad (4.17)$$

where $\mathbf{J}_t \in \mathbb{R}^{\sigma \times n}$ is known as task Jacobian. One time-differentiation is not enough to make the control inputs appear, therefore a second time differentiation is necessary

$$\ddot{\mathbf{t}} = \frac{\partial \dot{\mathbf{f}}}{\partial \mathbf{q}_m} \dot{\mathbf{q}}_m + \mathbf{J}_t(\mathbf{q}_m) \ddot{\mathbf{q}}_m = \mathbf{f}_t(\mathbf{q}_m, \dot{\mathbf{q}}_m, \ddot{\mathbf{q}}_m) + \mathbf{G}_u(\mathbf{q}) \mathbf{u}_J \quad (4.18)$$

where

$$\begin{aligned} \mathbf{f}_t(\mathbf{q}_m, \dot{\mathbf{q}}_m, \ddot{\mathbf{q}}_m) &= \frac{\partial \dot{\mathbf{f}}}{\partial \mathbf{q}_m} \dot{\mathbf{q}}_m - \mathbf{J}_t \mathbf{M}_m^{-1} (\mathbf{c}_m(\mathbf{q}_m, \dot{\mathbf{q}}_m) + \mathbf{g}_m(\mathbf{q}_m)) - \\ &\quad \mathbf{J}_t \mathbf{M}_m^{-1} \mathbf{J}_m^\top \mathbf{T}_m^{-1} (\mathbf{M}_o(\mathbf{x}) \ddot{\mathbf{x}} + \mathbf{c}_o(\mathbf{x}, \dot{\mathbf{x}}) + \mathbf{g}_o(\mathbf{x})) \\ \mathbf{G}_u(\mathbf{q}) &= \mathbf{J}_t(\mathbf{q}_m) \mathbf{M}_m^{-1}(\mathbf{q}_m) \underbrace{[\mathbf{I}_n \quad \mathbf{J}_m^\top \mathbf{T}_m^{-1} \mathbf{G}_t(\mathbf{q})]}_{\mathbf{A}} \end{aligned}$$

and $\mathbf{u}_J = [\mathbf{u}_m^\top \quad \mathbf{h}_t^\top]^\top$. Given our assumptions, the matrix $\mathbf{G}_u$ is full row-rank whenever $\mathbf{J}_t$ is full row-rank, because by construction $\mathbf{A}$ is the projection of $\mathbf{u}_J$ on the manipulator joints and $\mathbf{M}_m^{-1}$ is full rank by definition. From the structure it is also clear that the inputs directly related with the task dynamics are the manipulator torques, $\mathbf{u}_m$, and the concatenated force vector $\mathbf{h}_t$, that will be generated by the thrust magnitudes $\mathbf{u}_t$ and the moments $\mathbf{u}_r$ of the MRARs, through (4.1)-(4.2). At this point we are interested to enforce task trajectory tracking through a control action $\mathbf{u}_E \in \mathbb{R}^\sigma$ such that

$$\mathbf{u}_E = \ddot{\mathbf{t}}_d + \mathbf{K}_D \dot{\mathbf{e}} + \mathbf{K}_P \mathbf{e} - \mathbf{f}_t \quad (4.19)$$

where $\mathbf{e} = \mathbf{t}_d - \mathbf{t}$, $\mathbf{K}_D \in \mathbb{R}^{\sigma \times \sigma}$ and $\mathbf{K}_P \in \mathbb{R}^{\sigma \times \sigma}$ are diagonal positive definite matrices. To implement $\mathbf{u}_E$, $\mathbf{u}_J$ has to verify

$$\mathbf{G}_u \mathbf{u}_J = \mathbf{u}_E, \quad (4.20)$$

in order to be plugged in (4.18) to ensure the tracking of a desired trajectory $\mathbf{t}_d$. Thanks to redundancy there are infinite possible input allocations, $\mathbf{u}_J$, for a given $\mathbf{u}_E$. It is then possible to choose $\mathbf{u}_J$ so to respect all the system constraints and take advantage of the system redundancies.

In order to do so, we formulate the control problem as a programming problem to minimize the cost function $\mathcal{J} : \mathbb{R}^{(n+3k)} \mapsto \mathbb{R}$ defined as

$$\mathcal{J}(\mathbf{u}_J) = \mathbf{u}_J^\top \mathbf{P} \mathbf{u}_J, \quad (4.21)$$

where $\mathbf{P} \in \mathbb{R}^{(n+3k) \times (n+3k)}$, defined as $\mathbf{P} = \text{diag}\{\mathbf{J}_t \mathbf{J}_t^\top, \mathbf{P}_t\}$, is a weighting matrix to allocate the forces according to the maximum torque of the manipulator motors and MRAR thrusters, and in order to increase the force manipulability ellipsoid described by matrix $\mathbf{J}_t \mathbf{J}_t^\top$, see [105]. The matrix $\mathbf{P}_t \in \mathbb{R}^{3k \times 3k}$ allows, if needed, to weight MRARs differently from each other and from the robot manipulator. The solution of the optimization problem is constrained by $\mathbf{u}_J \in \mathcal{F}$, where $\mathcal{F}$ is the feasible solutions set defined by the inequalities (4.12), (4.14), and (4.15) plus $\mathbf{u}_J$ should satisfy (4.20) which yields the constraint

$$\boldsymbol{\xi}(\mathbf{u}_J) = \mathbf{G}_u \mathbf{u}_J - \mathbf{u}_E = 0 \quad (4.22)$$

where $\boldsymbol{\xi} : \mathbb{R}^{n+3k} \mapsto \mathbb{R}^\sigma$. Note that the constraint (4.13) is addressed by the task choice. In summary, the control allocation problem is

$$\begin{aligned} \mathbf{u}_J^* = \arg \min_{\mathbf{u}_J} \quad & \mathcal{J}(\mathbf{u}_J) \\ \text{s.t.} \quad & \chi_i(\boldsymbol{\eta}_i) \leq 0 \quad i = 1, \dots, k \\ & \|\mathbf{h}_i\| \leq h_i^{\max} \quad i = 1, \dots, k \\ & \min(u_m^i) \leq u_m^i \leq \max(u_m^i) \quad i = 1, \dots, n \\ & \boldsymbol{\xi}(\mathbf{u}_J) = 0. \end{aligned} \quad (4.23)$$

All bounded constraints, equality and inequality, are affine functions of the optimization variable $\mathbf{u}_J$, and since $\mathcal{J}(\mathbf{u}_J)$ is convex quadratic, (4.23) is a convex programming problem. A wide range of efficient methods could be used to solve the problem, see, e.g., [?]. This takes advantage of the system redundancy to satisfy all the system constraints in an optimized way while following a desired trajectory.

Our knowledge of the system dynamics being subject to some uncertainties, e.g., changing the orientation of the MRARs is changing the Inertia of the last link, as we considered the weight and Inertia of the system (object and MRARs). There might also be some parametric uncertainties such as imprecise weight and length measurements. unmodeled dynamics, such as motor dynamics are another source of uncertainty. In order to cope with unmodeled dynamics and parametric uncertainties a disturbance observer is utilized.

Let $\hat{\mathbf{f}}_t$ be the nominal value of $\mathbf{f}_t$ that represent the existence of a lumped bounded

uncertainty in the model. The following disturbance term can be introduced

$$\mathbf{d} = \mathbf{G}_u^+(\ddot{\mathbf{t}} - \hat{\mathbf{f}}_t) - \mathbf{u}_J \quad (4.24)$$

and the second order task dynamics, (4.18) can be rewritten

$$\ddot{\mathbf{t}} = \hat{\mathbf{f}}_t + \mathbf{G}_u(\mathbf{u}_J - \mathbf{d}). \quad (4.25)$$

A common approach to estimate the disturbance is to use the following disturbance observer

$$\dot{\hat{\mathbf{d}}} = -\mathbf{L}\hat{\mathbf{d}} + \mathbf{L}\left(\mathbf{G}_u^+(\ddot{\mathbf{t}} - \hat{\mathbf{f}}_t) - \mathbf{u}_J\right) \quad (4.26)$$

where $\mathbf{L} \in \mathbb{R}^{(n+3k) \times (n+3k)}$ is positive diagonal observer gain, and $\hat{\mathbf{d}}$ is the output of the disturbance observer. This means that (4.20) rewrites as

$$\mathbf{u}_E = \mathbf{G}_u(\mathbf{u}_J - \hat{\mathbf{d}}), \quad (4.27)$$

and hence the optimization problem (4.23) as to be updated with

$$\xi(\mathbf{u}_J) = \mathbf{G}_u(\mathbf{u}_J - \hat{\mathbf{d}}) - \mathbf{u}_E \quad (4.28)$$

to take into account the disturbances. Using this control scheme we ensure task trajectory tracking, while the system redundancies are exploited to satisfy the system constraints and reject possible disturbances.

4.3.1 MRAR Attitude and Thrust Control

There are several efficient nonlinear controllers that could be used to generate the desired force vector with each MRAR [106]. We utilize the following controller

$$\mathbf{u}_t^i = \mathbf{z}_i^\top \mathbf{R}_i^\top (m_i g \mathbf{z}_w + \mathbf{h}_i) \quad (4.29)$$

$$\mathbf{u}_r^i = -\mathbf{K}_R \mathbf{e}_R^i - \mathbf{K}_\omega \mathbf{e}_\omega^i + \boldsymbol{\omega}_i \times \mathbf{J}_i \boldsymbol{\omega}_i \quad (4.30)$$

where $\mathbf{K}_R, \mathbf{K}_\omega \in \mathbb{R}^{3 \times 3}$ are diagonal gain matrices with positive elements, $\mathbf{e}_R^i$ is orientation matrix error as

$$\mathbf{e}_R^i = \frac{1}{2} \mathbf{S}^-(\mathbf{R}_d^{i\top} \mathbf{R}_i - \mathbf{R}_i^\top \mathbf{R}_d^i) \quad (4.31)$$

where $\mathbf{S}^-(\bullet)$ is the inverse operation of $\mathbf{S}(\bullet)$, and $\mathbf{e}_\omega^i$ is the angular velocity error defined as

$$\mathbf{e}_\omega^i = \boldsymbol{\omega}_i - \mathbf{R}_i^\top \mathbf{R}_d^i \boldsymbol{\omega}_d^i \quad (4.32)$$

where $\boldsymbol{\omega}_d^i \in \mathbb{R}^3$ is the desired angular velocity. The desired rotation matrix is simply obtained by calculating the rotation matrix that transforms $\mathbf{z}_w$ to $\mathbf{h}_i/\|\mathbf{h}_i\|$, i.e., aligning the thrust direction to the load of the system on the corresponding MRAR.

4.4 Numerical Simulations

Numerical simulation for the case of a six degrees of freedom ground manipulator (anthropomorphic arm and a spherical wrist) cooperating with one quadrotor UAV is presented in this section to show the feasibility and effectiveness of the proposed scheme. The simulation has been performed in Matlab/Simulink environment utilizing the SimMechanics modeling toolbox, as illustrated in Fig. 4.4. The optimization problem is solved using Sequential Quadratic Programming (SQP) method. The simulation sample time is 1 ms, and the control loop sample time is 10 ms.

The length of the manipulator arms are respectively, 1.0 m for the first link and 0.7 m for the second. The total mass of the arm is 18.4 kg, and its maximum payload is 5 kg. In accordance with the actual Universal Robot UR5 robot, the maximum joint torques are [150;150;150;28;28;28] N m, from base to end-effector, and joint angle limits are $\pm 2\pi$ for all the joints. The simulated quadrotor, with 0.50 m distance between the diagonal motors, is actuated by four motor-propeller sets, each one can generate up to 10 N force, and the length of the arm that holds the gripper is 40 cm. We consider the spherical joints limit to be described by a cone of $\pi/4$ half cone angle. All the motors are modeled as a second order linear system with a 10 ms rise time.

The cooperative task is a trajectory tracking task with the load being a 5 kg bar of dimension $0.05 \text{ m} \times 0.2 \text{ m} \times 1 \text{ m}$. We consider the loading of the bar on the back of the mobile platform, where the robot is also mounted. The robot arm grasped the bar from one end and the quadrotor from the other end, with a 1-DoF gripper on its arm that is attached to its CoM. The task consists to follow an appropriate trajectory (generated through way-points and cubic-spline-based trajectory generator) to put the bar on the mobile base back. Such a scenario could be of interest in robotic search and rescue missions.

The control system is implemented considering a highly uncertain model, indeed some terms in the inverse dynamic used by the controller are neglected. The Inertial matrices are considered diagonal, and the Coriolis/centripetal terms are neglected. Furthermore 10% uncertainty is considered for the contact points.

The results of the trajectory tracking task are depicted in Fig. 4.5 and Fig. 4.6, that are the end-effector position measured with respect to the base of the arm. As it is evident from those figures the given trajectory is tracked sufficiently, even though the dynamic of the system was partially unknown. It is worth noticing that the arm manipulator alone is not able to perform this task, because of the torque constraints. Indeed the object weight is at the limit of the manipulator, but that does not guaranty that the weight generated torque at the end-effector will satisfy the joints limits. This is exhibited here as the

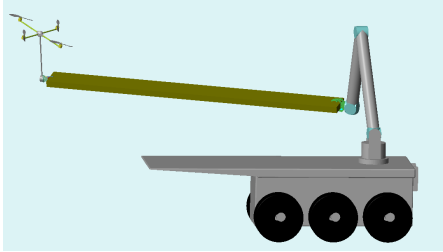


Figure 4.4: Simulation case study a ground manipulator and a quadrotor UAV cooperatively manipulating an object.

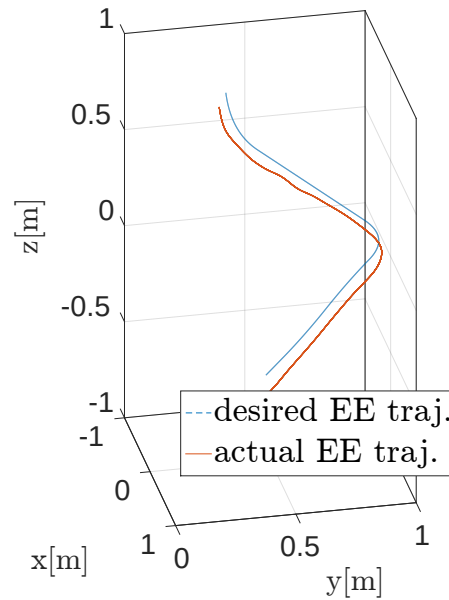


Figure 4.5: The desired and actual path of the end-effector in 3D.

arm has to grasp the object far from the object CoM. The arm manipulator desired and actual joint angles are plotted in Fig. 4.7, with the desired joint angles obtained through inverse kinematics for the task trajectory. One can see the weakness of the wrist joints (the higher errors of $q(4, 5, 6)$) in tracking the desired angles. However, thanks to the MRAR support the tracking task is performed sufficiently. The torque of the arm joints are shown in Fig. 4.7, and evidently the joint torques are far from their limits. Fig. 4.8 shows the quadrotor states and control inputs in the simulation. Fig. 4.8 top left is the orientation of the quadrotor which remains far away from the spherical joint limit, and Fig. 4.8 bottom left are the associated control torques. Fig. 4.8 top right illustrates the output of the optimal force allocation algorithm for the quadrotor, that is a desired force vector h_t . This force vector is then generated by u_r and u_t which are the moments and thrust of the MRAR, which are shown in Fig. 4.8 bottom right and left, respectively, and again they all satisfy the constraints of the system.

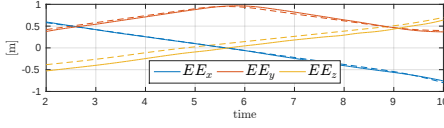


Figure 4.6: The desired and actual position of the end-effector.

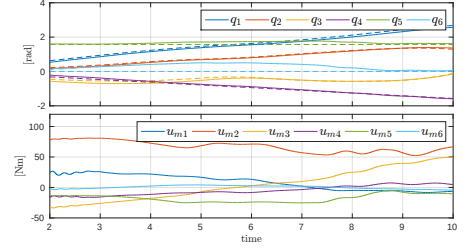


Figure 4.7: The allocated joint torques and the resulting joint angles satisfy the arm manipulator constraints.

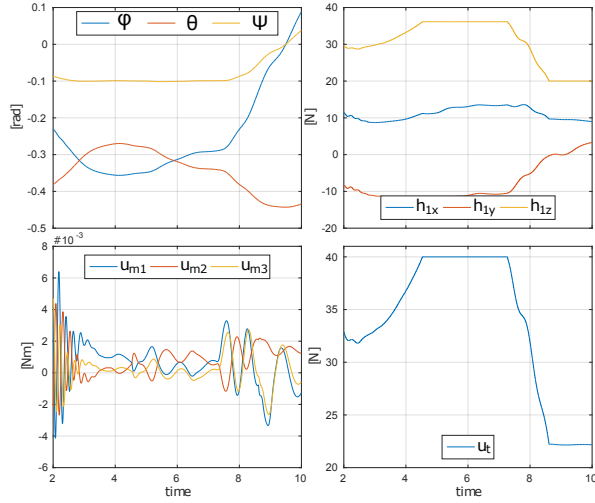


Figure 4.8: Quantites related to the Aerial Robot from simulation. On the left, the MRAR orientation and the associated control torques, u_r . On the right, the output of the force allocation for the quadrotor h_t and the MRAR thrust magnitude generated along MRAR's z -axis.

4.5 Preliminary Experimental Results

The preliminary experimental work associated to this chapter demonstrates the feasibility of MAGMaS. In this first step we consider a fixed arm manipulator and an aerial manipu-

lator. The aerial manipulator is the same platform of the previous chapters, fitted with a custom passive rotational joint. This passive rotational joint ensures that the center of mass of the MRAR plus joint system and the rotation center of the joint are coinciding, modulo manufacturing imperfections. This is of paramount importance as the MRAR cannot sustain high torque disturbances. From the design, the rotational joint has the following angular constraints, two rotations are limited to $\pm 40^\circ$ and $\pm 20^\circ$ respectively and the last one is free, note that contrary to the simulation part the base of the joint cone is not a circle but an ellipse as the two rotations constraints are not symmetric. We choose the load to be a wooden bar of length 2.5 m and mass 0.61 kg, as the focus is on the joint design validation. Also, as the grasping of the object is omitted, all sub-systems are rigidly attached together. The full system is depicted in Fig. 4.10. As a first validation of the MAGMaS, we propose to compare the handling of the considered bar with and without the help of an MRAR. The end-effector is moved up and down along the z -axis, see fig. 4.9 and Fig. 4.12–4.13 where the relevant quantities are plotted. Note that this comparison is possible because the bar characteristics are not violating the LWR4 payload/torques limits. Clearly the addition of the MRAR allows the bar tip to better follow the arm trajectory, the residual difference comes from the simple way we used to deal with the bar flexibility, proper handling of the flexibility is not addressed in this chapter and would improve the performance.

4.6 Conclusion

In this chapter we introduced a new kind of multi-robot system, the Multiple Aerial-Ground Manipulating Systems, shortly called MAGMaS. The motivation is to benefit from the advantages of both kinds of platforms, i.e., physical strength for the manipulator versus large workspace for the aerial robots, to accomplish manipulation tasks. For this new kind of system we derived the associated model, and considered a set of tasks taking advantage of the system structure. We derived a static feedback linearization control schemes which exploits the system redundancies to concurrently ensure trajectory tracking, system constraints respect, and model uncertainties. Trajectory tracking has been proven successful in realistic numerical simulations. Finally we presented experiments of a preliminary system, validating MAGMaS approach and mechanical design.

Extension of the proposed autonomous system to teleoperated and shared control systems (Tele-MAGMaS) are the next ongoing steps of the work.

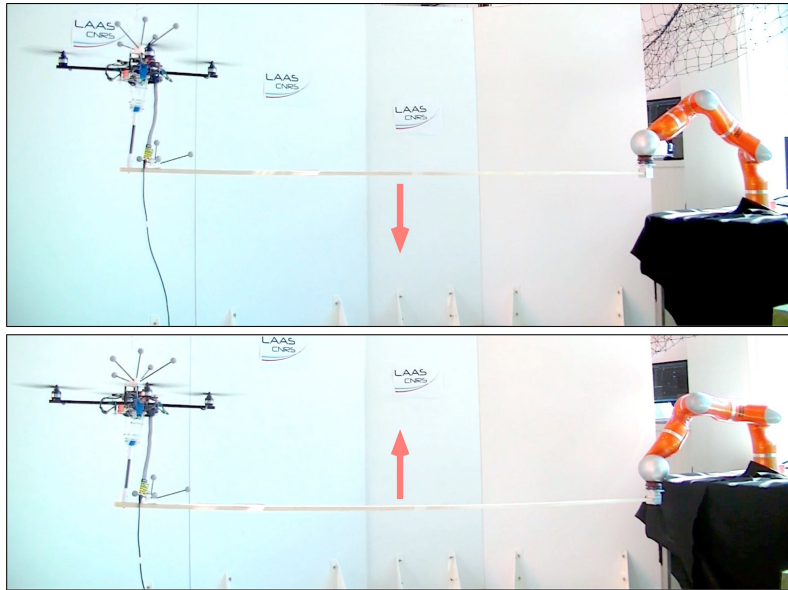


Figure 4.9: Experimental set up consisting of a KUKA LWR4 arm, a quadrotor and an in-house designed passive rotational joint. The two extreme configurations of the up-down trajectory are depicted in with the bar hold horizontal, the MRAR and the KUKA arm cooperatively elevate and lower the horizontal bar. Second experiment with the bar tilted, where the MRAR hovers while the KUKA arm tilts the bar in order to exhibit the decoupling induced by the passive rotational joint. And close up on the passive rotational joint design while in action.

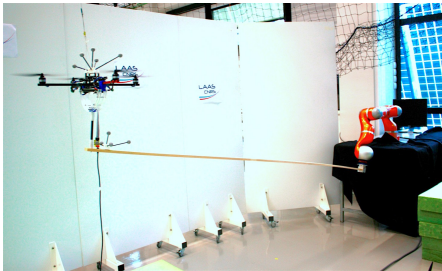


Figure 4.10: Cooperative manipulation of long flexible bar by a heterogeneous robotic team composed of a robotic arm and a quadrotor MRAR.

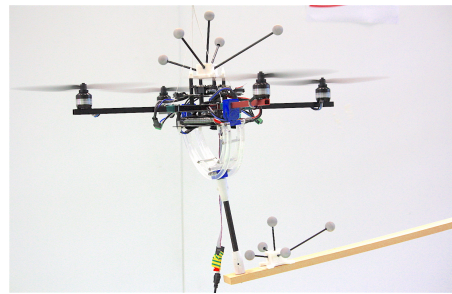


Figure 4.11: Spherical joint that is designed for the experiments with wide operating range.

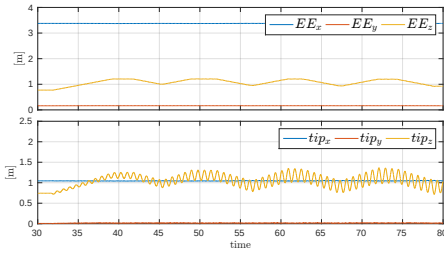


Figure 4.12: The arm end-effector follows a vertical trajectory without the help of a quadrotor. The tip position is vibrating a lot due to the flexibility of the bar and the tip is not able to track the end-effector z -trajectory.

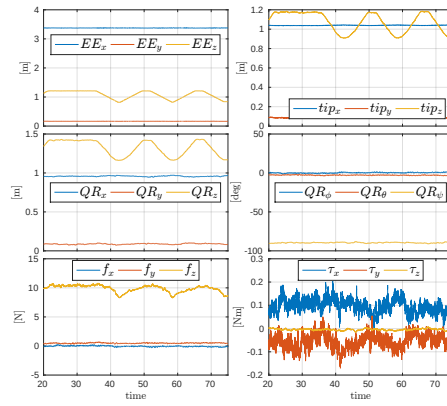


Figure 4.13: The arm end-effector follows a vertical trajectory, in cooperation with a quadrotor (QR). The tip of the bar follows the z -trajectory of the end-effector thanks to the quadrotor stabilizing action.

Conclusions and future work

The present Thesis addresses aerial tele-manipulation. In this chapter, the main contributions presented by this Thesis to the challenging robotic research fields of aerial robots, tele-robotics, and cooperative manipulation are summarized. The main achievements of this research work are highlighted, and possible directions for future works are the last points of this dissertation.

Conclusions

The idea of using Multi-Rotor Aerial Robots (MRAR) for aerial manipulation is the core of the Thesis. In order to utilize most of the robot power to perform the real work, and not to carry a heavy arm, and for some other reasons such as: increasing the flight time, reducing the costs, simplifying the mechanical structure— such that the current commercial vehicles can be utilized for aerial manipulation— we used lightweight passive arms as an end-effector mounted on the top or below the MRAR. The importance of human role in real robotics scenarios in unstructured environment, situations like human-robot-teaming in Urban Search And Rescue (USAR), is irrefutable. Thus all of the aerial manipulation schemes presented in this Thesis, either single vehicle or team of robots, are tele-operated by a human operator, which also enjoys the haptic feedback increasing his situational awareness depending on the states of the system in remote side.

In Chapter 2 a single MRAR equipped with a lightweight passive arm, that is composed of a rigid bar attached from the top to the vehicle and a compliant spherical joint that connects an end-effector to the bar. The end-effector has a wide surface with high friction and a shock-absorber on surface of end-effector s considered in order to establish smooth contacts. A human operator using a multi-degree of freedom haptic device drives the vehicle in both free flight and in contact conditions. In the free flight condition (without contact to the environment) the position of the master robot (haptic device) specifies the velocity of the MRAR, and in this way the problem of unmatched workspace of master an slave is solved, and once in contact the position of the haptic device determines the desired force vector to be applied to the object by MRAR. A parallel position/force

control of is taking care of regulating both position and force. The control scheme for force regulation relayed on the force measurement of the force sensor. This force sensor also provide a signal to distinguish between free flight and contact condition, that is needed to interpret the master device motion appropriately, i.e., velocity in free flight and force in contact. Contact maintenance during the contact interaction has carried out by keeping the reference force vector in the friction cone of the contact. The outer force controller loop provides an external reference for position of the robot– by means of a proportional integral controller that acts on the error of the force– that is added to the main position reference of the robot. The experimental result demonstrated the efficiency and high performance of the proposed control scheme to utilize the proposed simple mechanical structure.

In Chapter 3 a fleet of MRARs equipped with lightweight passive arms is utilized for cooperative aerial manipulation. The arm– that is composed of a lightweight rod and an end-effector with adhesion mechanism– is attached to the vehicle from bottom through a spherical joint that is coupled with a lock-and-release mechanism that locks the spherical joint in free flight, thus all components of the arm are fixed with respect to robot body in the free flight, and once a contact on the end-effector is established , based on a signal from a micro-switch on the end-effector, the mechanism releases the spherical joint, thus the MRAR that now is attached to the object, can rotate over the spherical joint that connects the arm to its CoM. Then, a team of MRARs that have attached the object from different contact points (that are known but uncertain) compose the slave side of a teleoperation system. On the master side a human operator drives the whole team in the remote side by means a multi-degree of freedom actuated haptic device. The position of the master robot, specifies the desired velocity of the object. And, a pose controller calculates the desired wrench– that if applied to the object by all the MRARs, the object tracks the desired trajectory commanded by the human operator. An optimization based force allocation algorithm specifies the contribution of each MRAR a force vector, by considering the constraints of the system. Once the desired force vector of an MRAR is calculated, an attitude and thrust controller calculated the appropriate total thrust and the suitable orientation of the vehicle to achieve the specified force vector. Human in the loop simulations and experimental results with real quadrotors showed the feasibility and effectiveness of the proposed control framework and grasping mechanism in aerial transportation.

In Chapter 4 a cooperative frame work is suggested that utilizes an arm robot manipulator in conjunction with an MRAR or fleet of them, and in this way we may enjoy the benefits of both type of the robots: power and precision of arm manipulators and extremely large workspace of MRAR. Another lightweight passive arm is utilized and in

this chapter, that is using a simple 1-DoF gripper as end-effector (that can grasp objects firmly) and attached to the MRAR from below using a customized spherical joint that can cover half of the rotation space. The core of the control scheme is similar to the slave side of Chapter 3 in which a pose controller calculates the total wrench and a force allocation algorithm assigns the proper force to each robot, with the following differences: a disturbance observer compensates for model uncertainties, the constraints of the system are different, the degrees of freedom of the robots differs (the arm might be any number greater than 1, and the MRARs have three DoF in generating force vectors), the optimization in this chapter is performed to maximize the manipulability ellipsoid of the system, while in the previous chapter the objective function aimed the minimizing the amplitude of forces and their derivatives. The attitude and thrust controller of the previous chapter are applied here as well with minor modifications. Simulation and preliminary experimental results have shown the effectiveness of the proposed cooperative robotic configuration, validated the modeling, and demonstrated the feasibility and efficiency of the proposed control approach.

Future work

Aerial manipulation is a sapling in robotic field. The present Thesis has provided some essential bases to raise the young plant. The following suggestions can be the next steps in this topic. The suggestions for future works are categorized and ordered according to the chapters of the Thesis. To improve the work present in Chapter 2 the suggestions are as follows:

- ◇ Considering the common possible communication network imperfections such as a time delay and packet lost in evaluation of stability and performance of the system.
- ◇ Utilizing adaptive control laws to cope with geometric asymmetries of the system in free flight, that might be very useful in case of using arms with not negligible weight.
- ◇ Novel high performance observer that can work even while agile motions of the robot in contact and contact free conditions might be very useful to avoid using force sensors.
- ◇ Utilizing more advanced control schemes, e.g., non-linear model predictive control, for force tracking in case of moving objects could be a remedy for poor performance of the system in case of moving objects, compared to fixed objects.

- ◇ Vision based control for this system is certainly the next step to bring the system to real world, where there is no external positioning system such as Vicon tracking system.
- ◇ Shared control can improve the performance of the system in some scenarios that the overall task is specified, e.g., the path is specified in an existing map of a house, but some human intervention might be unavoidable, e.g., the existing map has been messed up with furniture.

Suggestions to enhance the work presented in Chapter 3 are listed below:

- ◇ A grasp planning algorithm that assigns the best contact point to each robot depend on the object shape and number of the robots, is demanding.
- ◇ Design and implementation of new kind of formation control, in order to establish the planned grasp, in free flight for underactuated MRARs.
- ◇ Using the knowledge of the system, i.e., where is each robot and what are its states, in order to improve the robustness of the system in position and force control in the presence of aerodynamic disturbances from the teammates, is an interesting control problem.
- ◇ Using new adhesive mechanism and material can generalize the present approach with current mechanical structure to broader range of objects.
- ◇ Using uni-lateral contacts with no gripping or adhesion mechanism, e.g., deploying the mechanical structure of Chapter 2 for the cooperative scheme of Chapter 3, can extend the applicability of the system significantly, subject to use strong enough MRARs.
- ◇ Using Wearable haptic devices, such as gloves, and thimble can improve the efficiency of the teleoperation control scheme by making the human robot interaction more intuitive and natural.
- ◇ Decentralized control approaches might prepare the system for real autonomous scenarios.

And, finally here are some suggestion to continue the work of Chapter 4.

- ◇ Including the human operator into the control loop, thus making it teleoperation, will make the system more feasible for real situations.

- ◇ Shared control, in which a human operator modify a pre-planned task, may further improves the performance of the system for real scenarios.
- ◇ Since in the proposed robotic configuration (MAGMaS) suggested in the Chapter 4 the main source of manipulation and power is the arm manipulator, Leader-follower control approach can be a good candidate to go further than current centralized control approach.

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This Thesis focuses on bilateral aerial tele-manipulation and studies the aerial manipulation with Multi-Rotor Aerial Robots (MRAR). Differently from other approaches that are considering an arm and a hand mounted on an aerial vehicle, we propose lightweight passive arms that are installed on the vehicle either rigidly or through multi-degrees of freedom joints. The manipulation capability for the arm is provided by the motion of the MRAR. Using this lightweight passive arms allows to utilize the power of small size MRARs more for manipulation purposes rather than tolerating the weight of the arm. The MRAR equipped with the lightweight passive arm can perform force tracking tasks simply, i.e., can apply desired force vectors to the objects in environment. Then, more complex tasks are possible by utilizing a team of MRARs, in which each robot plays the role of a finger, making the flying hand dexterous to perform manipulation tasks. In order to cope with unknown, unstructured environment tele-operation approach is chosen. Moreover, to enhance the situational awareness of the user from remote side, bilateral teleoperation approach is used in which the human operator is provided with haptic feedback in the force form. This Thesis is organized to follow the same structure used in the described research: i) theory, ii) simulation, and iii) experiments.