Tele-MAGMaS: an Aerial-Ground Co-Manipulator System

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I. INTRODUCTION

The manipulation of large size objects by robotic systems is a challenge for applications in the field of construction industry, industrial decommissioning, and Urban Search and Rescue (USAR). These are associated to dangerous environments and thus motivate the need of devising robotic solutions for replacing human presence. Furthermore, they often require manipulation of long objects, such as pipes, bars, beams and metal frameworks, with limited access to their center of mass (CoM).

Robotic object handling has been tackled using (mobile) *ground manipulators* (GM). The rich literature on GMs proposes solutions with single or multiple robots for, *e.g.,* cooperative transportation of large objects [1], offshore robotic sensing and manipulation [2], or for cooperative assembly [3]. The use of GMs has two major drawbacks: first, typical small industrial manipulators have limited joint torques, resulting in poor maximal admissible Cartesian torques at the end-effector (EE) and second, GMs have a rather small workspace around their base, reducing their manipulation capabilities. These limitations can be particularly problematic for long objects if the GM cannot grasp them by their CoM, as that demands high torques at the EE and large workspace.

An emerging approach is the use of *aerial manipulators* (AM) for construction and large load handling. This has been made possible by the recent developments in *Unmanned Aerial Vehicles* (UAVs) control, especially the latest progress in the field of physical interaction, see *e.g.,* [4] for a panorama of the field. Their use has been demonstrated, in cooperative load transportation using cables [5], [6] (splitting the overall payload among members), in multi-robot assembly [7], [8], and aerial manipulation [9]–[11]. A major drawback of these platforms is their limited payload.

In this paper, we present a novel class of heterogenous systems which tackles the problem of manipulating long objects that cannot be grasped close to their CoM. Such systems go beyond the limitations of the previous approaches by leveraging the advantages of both AMs and GMs together. The small payloads of the AMs are compensated by the strength of the GM, while the limited workspace and poor Cartesian torque at EE of the GM is balanced by the virtually unlimited workspace and the favorable lever provided by AMs. The AM act as *Flying Assistants*, as they assist the GM from the air. The proposed class is called *Tele-MAGMaS*, where MAGMaS stands for 'Multi Aerial Ground Manipulator System' and Tele reflects the tele-operation capabilities, in fact, such systems also allow for remote human operation at different autonomy levels. The presence of a human operator, who owns superior intelligence and cognitive capabilities, is necessary in most of the realistic applications to cope with unknown/partially known environments with possibly unpredicted events. In the proposed Tele-MAGMaS scheme the human operators are also provided with haptic feedback to enrich their tele-presence and improve their performances.

Loosely related to the Tele-MAGMaS concept, a theoretical scheme for cooperative transportation between an AM and a mobile cart has been presented for the planar case in [12]. Another scheme with GM and tethered UAVs is presented in simulation in [13]. The Tele-MAGMaS concept considered in this work consists, instead, of two real world manipulators – aerial and ground, respectively, and with any number of degrees of freedom (DoF) – which have to perform a real manipulation task.

This paper highlights the key components of *Tele-MAGMaS* and demonstrates practically the implementation of the described algorithm in software and hardware for aerial-ground co-manipulation. Theoretical groundings are discussed in our previous works [14], [15]. To the best of our knowledge, this is the first time a *Flying Assistant* has been implemented. In particular, for the first time a cooperative manipulation task between a ground industrial manipulator and an aerial manipulator has been robustly demonstrated.

The design, architectural and experimental aspects raise many scientific and technological challenges. Indeed, a cooperative manipulation implies the exchanges of forces which need to be handled carefully to ensure system stability. Additionally experimental validation asks for robustness to model imperfections and over non-linearities. Based on our experience we felt the necessity to develop our own fully-actuated AM, able to resist external forces disturbances without changing its orientation and with an extra aperture for object manipulation. The proposed system is over-actuated w.r.t the task and the

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leveraging of redundancy in the system is not straightforward. In particular, attention to all actuation constraints is necessary during the cooperative manipulation. Also, the integration of the human operator needs to be handled with care, so that no provided commands can push the system beyond its limits and in unstable configurations. This requires careful analysis of the system behavior and the construction of safety margins around the operator behavior. The high complexity of the Tele-MAGMaS necessitated to develop software in a modular way in order to allow easier development, this required the careful design of the full software architecture used in this work, which implements a control framework allowing for the different modalities of *i)* full autonomy, *ii)* tele-operation and *iii)* shared control of the system, thus allowing the system to cope with the different complexity levels of various environments by also leveraging (when needed) the cognitive abilities of a human operator.

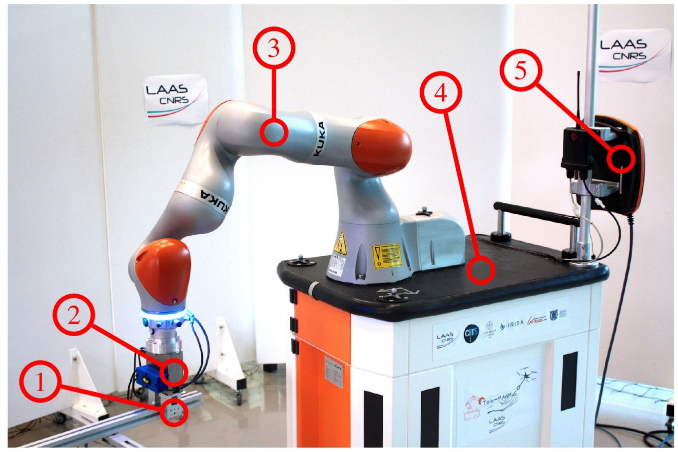

Fig. 1: Experimental setup with an LBR-iiwa (3) mounted on a FlewFellow (4). The smartPad (5) is carried by the FlexFellow (4) and the gripper (2) grasps the bar via custom-made claws (1).

II. Robotic Sub-Systems

In this section, we present the three robotic systems that compose the Tele-MAGMaS, the complete system depiction can be found in the Technical Report attached in the multimedia material. The GM is a state-of-art industrial manipulator, the AM is a custom platform, called OTHex, specifically designed for bar lifting. Lastly, the haptic interface is a commercial delta manipulator, with force feedback capabilities. The three robotic systems have all been chosen following the principles exposed in the Technical Report attached in the multimedia material.

A. Ground Manipulator – LBR-iiwa

As GM we used the 7-DoF *LBR-iiwa 14 R820*, allowing a 14kg payload and 820 mm reach (see Tab. I for more data), this satisfies the task requirements for the GM in terms of payload and workspace, see the attached Technical Report. The embedded joint torque sensors allow to retrieve the external wrench without the need to integrate a F/T sensor at the EE. Despite the significant payload, its maximum admissible joint torques for the last joins is 40 N and its rated torque of 23.3 N m corresponds to holding horizontal a 1.42 kg bar of length 3 m, which may not reflect typical bar-weight for several of the considered applications.

The software architecture of the LBR-iiwa is dictated by the proprietary solution. The control cabinet contains two computers, a Windows machine for the high-level interface and a Vx-Work machine for real-time execution of the applications. In our setup, we use a KUKA library, called FRI for Fast Robot Interface, which uses UDP to achieve real-time control from a remote computer. The application on the control cabinet runs a server, while also running the low-level safety features, to which the client sends commands at high frequency (up to 1kHz) and receives system information. In this modality, the remote computer has access to various quantities in order to close the control loop and sends joint commands to a low-level joint control loop that runs on the control cabinet. This allows real-time interaction between the operator and the manipulator. Any other manipulator would have worked as long as hard real-time remote control is supported.

During our implementation only the joint controllers (position or impedance) were available in the FRI library. Hence we built our control architecture on top of the joint position controller, by implementing both an admittance filter and an inverse kinematics layer. For compliance, admittance filter is preferred over impedance control despite being more tedious to tune, because of the availability of low-level position controller, see [16]. That means that the new, compliant, reference trajectory for the EE pose is decoded into joint trajectory based on closed-loop inverse kinematics [17].

As for the gripper, we integrated a Schunk *PGN-plus-E 80-1* gripper on the flange of the LBR-iiwa, with custom designed claws. The choice of this gripper was made considering the significant torques that could be involved at the EE during our experiments (as pointed out in the Technical Report).

B. Aerial Manipulator – OTHex

The *Open Tilted Hexarotor* (OTHex) is an aerial manipulator specifically developed for this project and tailored to perform physical interaction tasks with the environment, i.e.,

Description	**Value**	**Unit**
reach	820	[mm]
volume	1.8	[m^3]
weight	29.9	[kg]
position repeatability	± 0.15	[mm]
max. rated payload	14	[kg]
max. rated torque at EE	23.3	[N m]
max. joint angle	$[\pm170, \pm120, \pm170, \pm120, \pm170, \pm120, \pm175]$	[°]
max. joint angular velocity	$[85, 85, 100, 75, 130, 135, 135]$	[$^\circ\,\mathrm{s}^{-1}$]
max. joint torque	$[320, 320, 176, 176, 110, 40, 40]$	[N m]
FRI control frequency	500	[Hz]

TABLE I: Characteristics of the GM used in the experiments (KUKA LBR-iiwa 14).

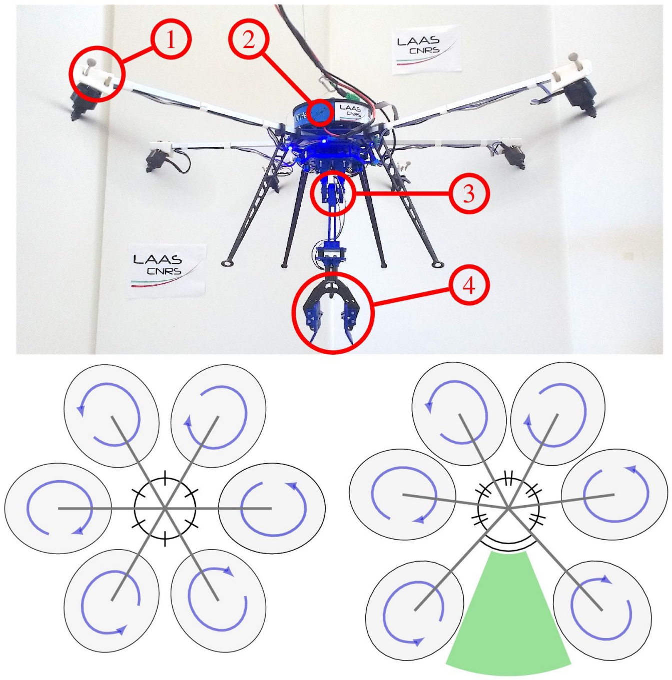

Fig. 2: Top, OTHex (hovering) with main features highlighted: one of the tilted motors (1), the electronics case (2), the passive joint (3) and the two coordinated grippers (4). Bottom, Comparison of the spatial location of the propellers for a standard hexarotor configuration and the OTHex. The OTHex configuration is such that an aperture of 85° is left to facilitate the manipulation of a long object (green area).

meeting the requirements presented in the Technical Report. Its main features and peculiarities are presented here, more details can be found in [15], while its key specifications are listed in Table II.

The first feature is the *tilted* propeller actuation. In classical multi-rotor design all the propellers are collinear, which leads to an *underactuated* system dynamics, i.e., position and orientation cannot be controlled independently. The OTHex design enforces non-collinear propeller orientation, as illustrated in Fig. 2-top. This design feature allows the system to have *multi-directional thrust ability*, i.e., the total thrust can be exerted in a polytope attached to the body frame instead of just along a single upward direction as in the underactuated case. This means that the robot can exert lateral forces without the need for re-orienting itself thus being able to track a decoupled reference trajectory in position and orientation, within the

Parameter	**Value**	**Units**
weight (without battery)	2.48	[kg]
extra payload	2.9	[kg]
actuation unit 1st tilt angles	35	[°]
actuation unit 2nd tilt angles	-10	[°]
autonomy (on battery)	15	[min]
max. lateral force (hovering)	8	[N]

TABLE II: Main quantities related to AM used in the experiments (OTHex).

physical limits of the actuators. Such a design is gaining popularity in the literature [18]–[20] mainly because the multi-directional thrust aerial vehicles are, by design, particularly well suited for physical interaction tasks. Indeed, they can exert a decoupled set of forces and torques on their environment, independently of the contact point position. In particular, this means that they can resist external disturbances while completing a manipulation task without the need to change their orientation, which could jeopardize the manipulation task itself.

The second feature of the OTHex consists of an aperture of 85° between two bars of its skeleton (see bottom Fig. 2). This configuration has been preferred over the regular hexagonal positioning of the actuation units to facilitate the manipulation of a long object, *e.g.,* a beam. Thanks to this unique design the object can pass through the aperture, allowing for a wider variety of beam manipulation tasks.

The extra payload of the OTHex AM can be used to assist the GM in the cooperative manipulation task. For example only 7 N at the end of the bar (0.25% of its extra payload) are sufficient to cooperatively transport a 3 m bar of weight that fits the considered applications.

Lastly we designed a lightweight mechanical system consisting of a passive revolute joint with two grippers, which endows the OTHex with grasping and manipulation capabilities required to perform physical interaction. A passive joint has been preferred over an actuated one to reduce the complexity and weight of the system; this solution is viable thanks to the full-actuation of the OTHex. Indeed, in the studied use case, the OTHex acts as a *Flying Assistant* following the GM motion, hence a 1-DoF passive joint is sufficient to accomplish the task.

The OTHex control architecture is articulated over three main components: low-level controller, wrench estimator and admittance filter, whose details can be found in our previous work [15] and therein.

To guarantee robustness of aerial physical interaction, software compliance was necessary. We preferred admittance over impedance framework, for two main reasons: *i)* the availability of a precise pose controller for the OTHex and *ii)* the ease to enable/disable the software compliance during pose-based tasks. In practice, we did not experience the tuning drawbacks of admittance framework w.r.t. inconsistencies for steady state commands with different virtual inertia.

C. Haptic Interface

Human operators can interact with robotic systems via different interfaces, such as touch displays, game-pads and haptic devices. A haptic device (or haptic interface) is a robot that works in the master side of a tele-operation system. The human operator can move the master robot by applying force to its handle and reversely the haptic interface can apply forces to the human operator, called "haptic cues" or "haptic feedback." Haptic feedback is used to provide the human operator with information about the state of the remote system.

In our testbed, we used an Omega.6 haptic device, which has six DoFs, the three translations are actuated by independently controlled DC motors and the three rotations are passive. The device communicates through USB 2.0 with the main PC and can be controlled at up to 4 kHz (the faster the control loop the better the force rendering).

III. SYSTEM AUTONOMY FRAMEWORK

Following the discussion on system autonomy in the Technical Report, the Tele-MAGMaS has three distinct operation modes: *i) fully autonomous*, *ii) tele-operated* and *iii) shared-control*. In the following we review these approaches and we show how the human operator can assist or intervene in each approach by means of a haptic device.

A. Fully autonomous MAGMaS

The MAGMaS fully autonomous operation mode is targeted for when the system evolves in a well-structured fully known environment. It relies on two key components: a trajectory planner and finite state machine (FSM); which together compose the task planner, depicted in Fig. 3-top. The FSM is detailed in lower part of Fig. 3 and defines the policy used by the task planner for generating the robot motion trajectories and triggering the grippers actions, based on the robots and environment information and the operator. The autonomous cooperative manipulation phase (S_3) can be implemented in a centralized or decentralized way. In centralized cooperative manipulation, both robots are commanded based on the manipulated object position. A detailed description of this approach can be found in [14]. In this case, even if the proposed path planner relies on model inversion, the sensibility to parameter uncertainty and disturbance is mitigated via a disturbance observer, the compliant control of both manipulators and mechanical compliance. This made the full system reasonably robust to parameters uncertainties (see [15] for details on the OTHex side). In the decentralized modality, such as leader-follower approach, during the cooperative manipulation the GM manipulates the object and the flying manipulator assists the GM following its lead and producing an additional upward force on the bar.

B. Tele-operated MAGMaS

At the other hand of the autonomy spectrum, the bilateral tele-operation approach can be used to cope with unknown environment, uncertainties and also to facilitate completion of complex tasks. This is useful in scenarios like USAR, where MAGMaS must work in a partially or even completely unknown environment. In the bilateral tele-operation approach, skilled human operator drive the system in a precise and safe way while provided with force feedback in order to increase their situational awareness on the remote side.

In fact, in the bilateral tele-operation approach, the human intelligence performs the task planning with the help of visual and haptic feedback. If direct visual feedback is not possible, cameras can be mounted on the robots. In the non-cooperative parts of the task (S_1, S_2 and S_5) the human operator drives the robots, while in the cooperative part (S_3) the operator command the bar while the robots cooperatively manipulate

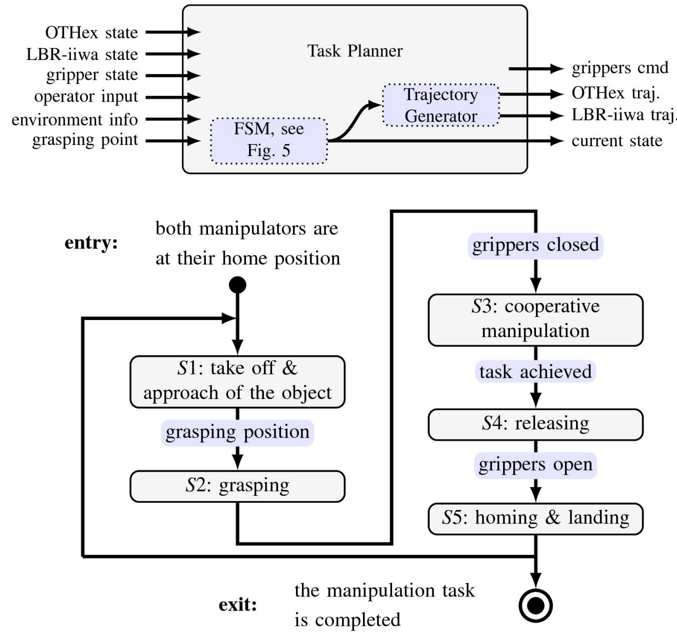

Fig. 3: Top, task planner inputs and outputs for a cooperative manipulation task performed by a Tele-MAGMaS. Bottom, the simple finite state machine (FSM) implemented in our task planner.

the bar to perform the human command. Gripper and state changes are manually triggered by the operator. In this case, the human intelligence decides how to move the robot, what are the suitable contact points, how to move the bar and along which path the robots should come back to their home position. The desired object pose and the current object state are sent to the object pose controller which computes low-level inputs for the robots' controller.

The operator is provided with a haptic feedback, $\mathbf{f}_{hap}$ (see Fig. 4), which depends both on the inertia of the whole system, through $\mathbf{f}_M$ and on a repulsive viscoelastic virtual force, $\mathbf{f}_o$, generated with the purpose of letting the operator feel the obstacles in the environment, this yields

$$\begin{aligned}\mathbf{f}_{hap} &= \mathbf{f}_M + \mathbf{f}_o\\ \mathbf{f}_M &= \mathbf{M}_{\boldsymbol{x}}\ddot{\boldsymbol{x}}\\ \mathbf{f}_o &= \mathbf{K}_P\mathbf{d}_{min} + \mathbf{K}_D\dot{\mathbf{d}}_{min}\end{aligned}$$

where $\mathbf{M}_{\boldsymbol{x}}$ is the inertia of the system projected at the objects point considered for the tele-operation, $\boldsymbol{x}$ and $\mathbf{d}_{min}$ and $\dot{\mathbf{d}}_{min}$ denote the shortest distance, components wise, toward an obstacle and its derivative and $\mathbf{K}_P$, $\mathbf{K}_D$ are two positive definite matrices chosen to generate the viscoelastic force. The total rendered force is saturated to satisfy the actuation constraints of the haptic device.

C. Shared-Control MAGMaS

The third possible autonomy level for the system is called shared control, which is the combination of the two previous approaches. An automatic task planner plans the motion commands and changes of logic states and the human operator can modify the planned trajectories. Human operator can locally change the trajectories or change the time law of the

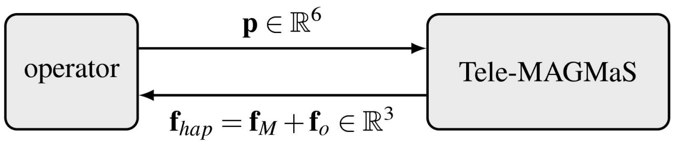

Fig. 4: Illustration of the bilateral tele-operation scheme, with operator commanding the position $\mathbf{p}$ and receiving a force feedback $\mathbf{f}_{hap}$ rendering the system inertia and proximity to obstacles.

trajectories for reacting to changes in the environment. This autonomy level is well suited for semi-structured environment, i.e., partially mapped environment, or fully mapped but with the possible occurrence of unpredictable events, *e.g.,* a construction site or an industrial environment where humans, robots and other machines work together.

IV. SOFTWARE ARCHITECTURE

The Tele-MAGMaS is composed by 3 main robotic parts, *i)* the LBR-iiwa arm, *ii)* the OTHex aerial manipulator and *iii)* the Omega.6 haptic interface, commanded by a centralized controller, which is interfaced with a simulator/visualizer.

In order to develop the experimental framework we relied on the GenoM3[1] abstraction layer, which allows defining middleware-independent software components for robotics (the middleware, *e.g.,* ROS, can then be chosen at compilation time). GenoM3 components are written in C/C++ and can be controlled via tcl-shell, Matlab command line, Matlab-Simulink or middleware specific means. This allows high flexibility in the development and use of the components.

The global software architecture is depicted in Fig. 5. The high-level control of the full system is realized in Matlab-Simulink, linked to the hardware via GenoM3 components (OTHex, Joypad, MoCap, LBR-iiwa) or Matlab S-function drivers (Haptic device, V-REP), which are C++ function natively interacting with Matlab. We chose this approach because we realized that development and test of controller in Matlab-Simulink is considerably faster than in pure C/C++. However, since Matlab-Simulink is not meant for real-time execution, the hardware is commanded via GenoM3 components. These GenoM3 components are essentially drivers for the hardware to satisfy real-time constraints as we chose to keep most of the algorithmic part in Matlab-Simulink. In order to satisfy the hard real-time constraints of the communication with the LBR-iiwa, inverse kinematics and other related utilities are performed in the GenoM3 component. In our architecture Matlab-Simulink runs at 500 Hz, the task/path planner (see Sec. III), the human input interpreter, the system state estimator and the OTHex controller all run inside Matlab-Simulink.

This component-based architecture allows easy repartitioning of the load between processes and machines. In our experiment, we chose to use ROS as middleware, which provides sufficient 'real-timeness' for the intended purpose. The component-based design also allows seamless change of the operator inputs, perception components or of the MAGMaS hardware, as each of those are separated from the main algorithmic part and provide standard interfaces which are not hardware specific.

[1]https://git.openrobots.org/projects/genom3/wiki

V. SIMULATION ENVIRONMENT

Simulation has to trade-off accuracy of the simulated behavior and computational load, weighted by the real-time constraint imposed by the human-in-the-loop control scheme. The chosen compromise is a multi rigid-body dynamics integration with collisions processing and reconfigurable joints. The physics simulation is handled by the software V-REP[2], a robot simulator providing a design environment and incorporating the simulation library Bullet. As the overall controller of the system relies on Matlab-Simulink, a bridge enabling bilateral communication between V-REP and the controller has been implemented, exploiting the the Remote API functions, which are integrated within S-functions in Matlab-Simulink, thus providing *data transceiver blocks*.

Additionally, a graphical user interface was implemented for providing some telemetry to the operator, both in simulations and during real experiments. The displayed information is a visual feedback, via emulated camera mounted on the OTHex, the interaction wrenches and general metadata about the sub-systems state. Considering the large amount of possible data to be shown, we have chosen to set up a hierarchical user interface, which allows the user to choose the level of detail. The operator is informed about the status of the system and sub-systems by means of color-changing indicators. Each detailed sub-window can be folded to reduce the visual load on the screen, see Fig. 6.

VI. EXPERIMENTS

The Tele-MAGMaS first experiments were showcased at the Hanover Fair 2017, as part of the finals of the KUKA 2017 Innovation Award, see Fig. 7. The demonstration presented the main features of the Tele-MAGMaS system and a proof-of-concept application. During the fair week, the demonstration was running every hour (or more), thus demonstrating the high reliability of the proposed system and control architecture. Videos highlighting the key features of the demonstration, i.e., cooperative aerial-ground manipulation with human tele-presence, can be found online[3,4].

Later on, we conducted a set of experiments with a successful co-manipulation of a 2.5 m long bar. The goal is to validate cooperative manipulation with a Tele-MAGMaS for both horizontal displacements of the object and lifting. These basic motions are considered to be representative of the possible construction/decommissioning scenario. Additionally the tele-presence framework is validated for tele-operation and full autonomy. The experiment sequence is depicted in Fig. 8 and consists in the following: at first the OTHex is manually flown to grasp the bar from one of its ends, while the ground robot autonomously grasps the other end. Once both manipulators are attached to the bar the co-manipulation is fully autonomous: they lift the bar from its supports, move

[2]http://www.coppeliarobotics.com/
[3]https://vimeo.com/217252361
[4]https://youtu.be/GRnGSvJGUKk

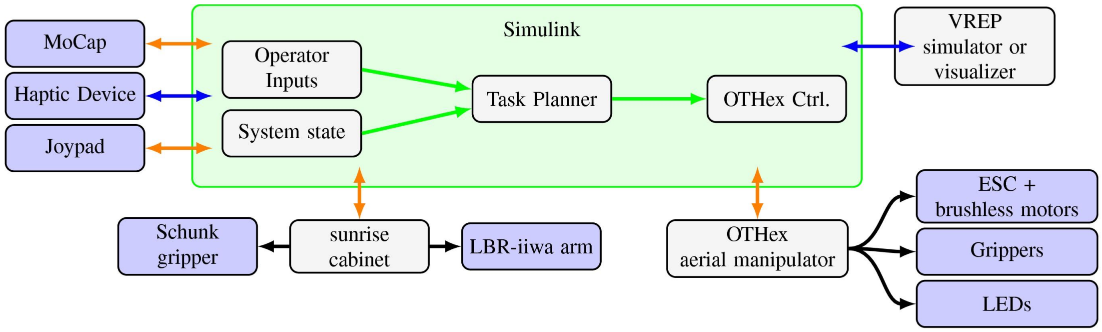

Fig. 5: Software architecture used in the Tele-MAGMaS project. In green Matlab-Simulink links, in blue C S-function links, in orange GenoM3 links and in black low-level links.

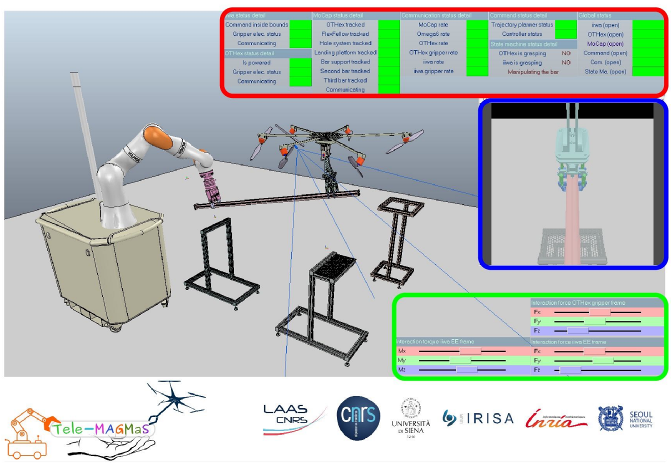

Fig. 6: Display of the 3D scene and graphical user interface within VREP, in red the sub-system status indicators (that can be folded), in blue the emulated FVP camera on the OTHex, in green the visualization of the interaction forces and torques.

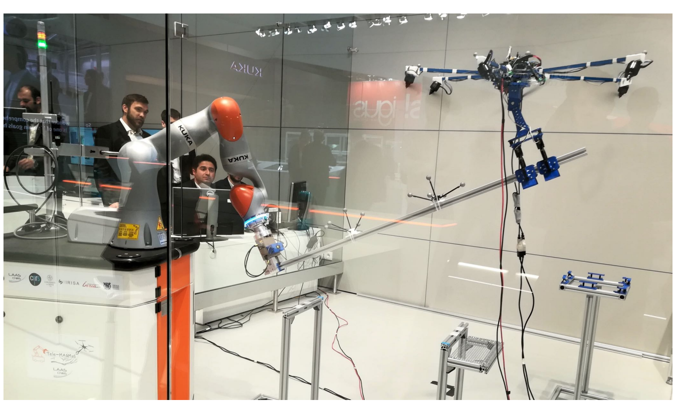

Fig. 7: A snapshot of the cooperative manipulation state of Tele-MAGMaS using bilateral tele-operation approach performed during the KUKA 2017 Innovation Award at the Hanover Fair.

it twice along a line in the horizontal plane (blue part) and then synchronously lift the bar up to 30° (green part). Then they bring the bar back to its starting position. This experiment highlights both the vibration stabilization induced by the OTHex and the feasibility of MAGMaS. Indeed we realized that the OTHex was subject to larger external forces than expected, *i.e.,* predicted by the model, due to vibrations of the long object. This is also illustrated in the video contained in the multimedia material. Key quantities of the system are displayed in Figs. 9-10. In particular, Fig.10 illustrates that a passive joint is sufficient to complete the task, as the bar motion is guided by the GM. Note that the small oscillation would have required some active suppression with an actuated joint, leading to more external wrench on the AM side. This implies that the passive joint as a stabilizing effect on the system. In Fig. 9 the Cartesian wrench at the GM end-effector is depicted (top), which transcribes the wrench exchanged between the manipulated object and the GM. Note that during the initial lifting of the bar from the stand there is a transient with oscillations which disappears during motion, this arises most likely because the model does not take into account the discontinuity of the object breaking contact with the stand, nevertheless, the system responds in a satisfactory manner. Also, note that the torque generated by the object's weight (τ_y) diminishes during the lifting of the object, as it is proportional to the cosine of the object inclination. The bottom part of Fig. 9 depicts the joint torque of the GM, it is clear that joint torques start to be noisy when the breaks are disengaged ($\approx$30 s). Given the particular configuration of the GM most efforts are furnished by the joint $A2$ (shoulder) and the three joints not aligned with the motion are not solicited ($A1$, $A3$, $A5$). All joint torques are well within their limits, see Tab. I. The AM desired trajectory from the admittance filter is presented in Fig. 10, the good tracking performances validate our approach. Indeed thanks to the multi-directional thrust the error in orientation does not impact the position during the cooperative manipulation.

VII. Conclusion and Future Work

We introduced a new kind of heterogeneous multi-robot system with a tele-operation capability, the *Tele-MAGMaS*. This new category of systems leverages the advantages of both mobile ground manipulators and aerial manipulators, in order to perform tasks which would be impossible for homogeneous systems. A scenario of object manipulation (pose tracking), out of the working conditions that a single robot could achieve, is enabled through the tele-operation of the MAGMaS. In order to demonstrate the benefit of aerial manipulators, we designed a fully-actuated platform tailored for bar lifting, the *OTHex*.

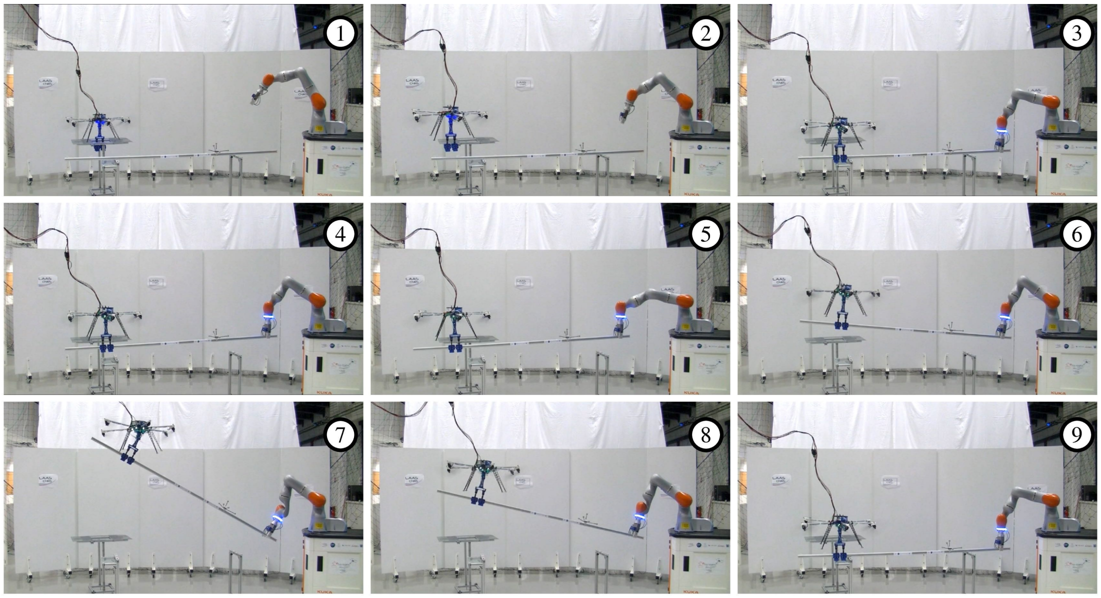

Fig. 8: Time-lapse of a MAGMaS cooperative manipulation task. Both robots are at their initial position (1), approach to the bar (2), grasping the bar (3), cooperative lifting (4), cooperative lateral motion (5), cooperative lifting up to 30° (6-7-8) and release of the bar (9). See attached multimedia for the corresponding video of the experiment.

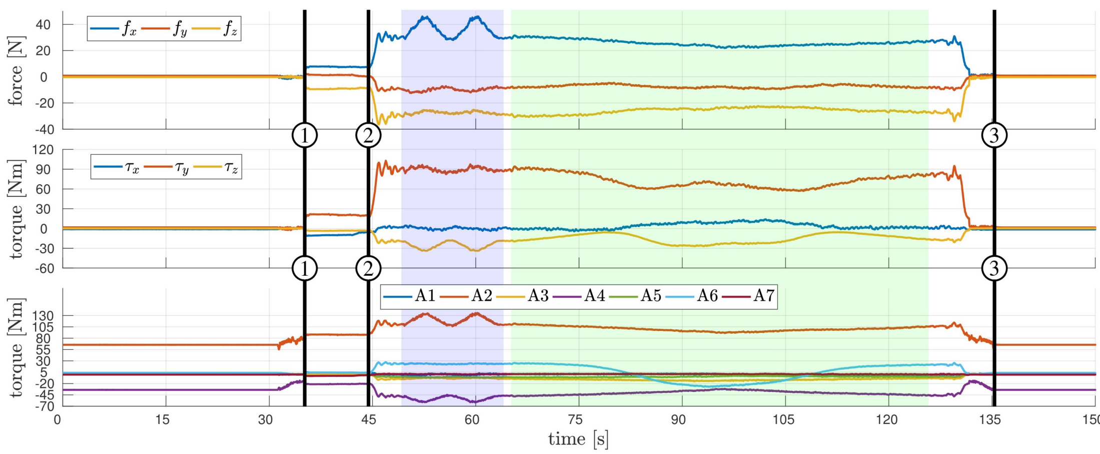

Fig. 9: On top and middle, external wrench as sensed from the joint sensors and projected on Cartesian space. Bottom, joint torques for each articulation of the LBR-iiwa. The three instants highlighted are LBR-iiwa grasping (1), cooperative lifting (2) and LBR-iiwa un-grasping (3). The blue part highlights the horizontal motion and the green part the bar tilting.

Integration and implementation of the framework have been demonstrated in a set of experiments (including a week of live demos during the 2017 Hanover Fair), thus proving the reliability of our approach. Moreover, the software architecture is component-based, hence adding higher-level task planner or other perception modules to operate outdoor could be easily obtained.

Aside from advantages provided by its architecture, the Tele-MAGMaS opens a new field of study, that may eventually bring improvements to the presented method. In particular, although the idea of Tele-MAGMaS is generic, further work is necessary to reach the point where three arbitrary robotic components can be strapped together as a viable Tele-MAGMaS for ad-hoc cooperative manipulation.

Currently, the system relies on the Motion Capture information for its localization and general state estimation: our goal is to replace the motion capture system with truly embedded perception in order to run experiments in any environment, especially outdoor. Our future work will also include the extension of the system and framework to a ground manipulator mounted on a mobile platform, which is of paramount importance in USAR or construction missions. It is also important to address the estimation of the load parameters and active rejection of vibrations in the system. Another envisioned plan to improve the work is to robustify the tele-operation and shared control schemes against time delay, to make the system usable in Internet-based tele-operation scenarios in which considerable time delays can occur during internet traffic jams.

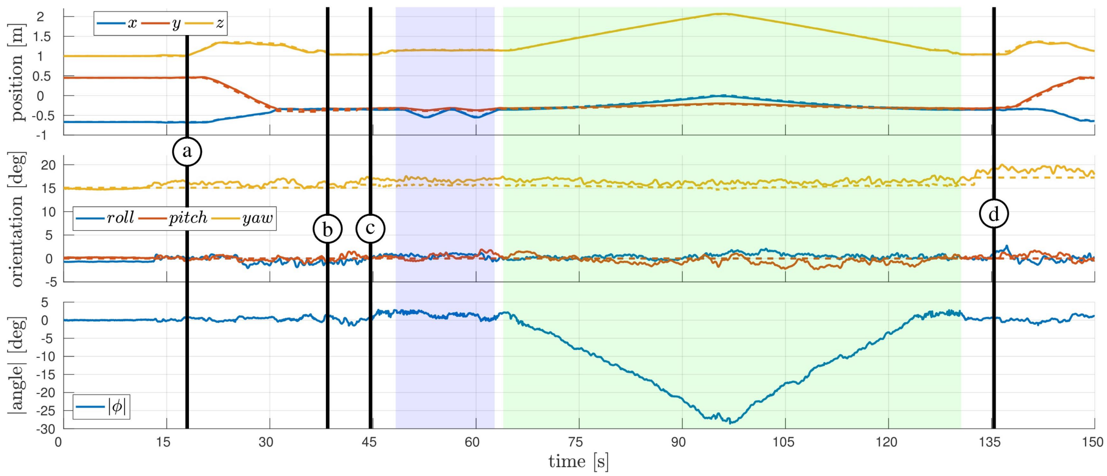

Fig. 10: On top and middle, position and orientation of the OTHex aerial manipulator. Bottom, evolution of the OTHex passive joint angle, during a typical task with free-flight, horizontal motion and object tilting.The four instants highlighted are take-off (a), OTHex grasping (b), cooperative lifting (c) and un-grasping(d). The blue part highlights the horizontal motion and the green part the bar tilting.

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