AFRL-AFOSR-UK-TR-2015-0031

Human-in-the-loop Control of Multi-agent Aerial Systems Under Intermittent Communication

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EOARD GRANT #FA8655-13-1-3055

Report Date: June 2015

Final Report from 27 March 2013 to 31 March 2015

Distribution Statement A: Approved for public release distribution is unlimited.

Air Force Research Laboratory
Air Force Office of Scientific Research
European Office of Aerospace Research and Development
Unit 4515, APO AE 09421-4515

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. REPORT DATE ***(DD-MM-YYYY)*** 8 June 2015	**2. REPORT TYPE** Final Report	**3. DATES COVERED** *(From – To)* 27 March 2013 – 31 March 2015

4. TITLE AND SUBTITLE

Human-in-the-loop Control of Multi-agent Aerial Systems Under Intermittent Communication

5a. CONTRACT NUMBER

5b. GRANT NUMBER

FA8655-13-1-3055

5c. PROGRAM ELEMENT NUMBER

61102F

6. AUTHOR(S)

Stjepan Bogdan

5d. PROJECT NUMBER

5d. TASK NUMBER

5e. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

FAKULTET ELEKTROTEHNIKE I RACUNARS
UNSKA 3
ZAGREB 10000 CROATIA

8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

EOARD
Unit 4515
APO AE 09421-4515

10. SPONSOR/MONITOR’S ACRONYM(S)

AFRL/AFOSR/IOE (EOARD)

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

AFRL-AFOSR-UK-TR-2015-0031

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution A: Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Results in designing and defining novel human machine interaction based on psychological measures as well as multiple source control inputs that utilize various communication channels. Decentralized Control of Multi Agent Systems with HMI. This is dedicated to robustness analyses of control systems (designed in other WPs) with respect to realistic communication network artifacts. Under the term realistic network artifacts, we refer to communication channels that distort exchanged information and introduce propagation delays, packet dropouts/collisions, and limited network throughput and communication range. The main goal of this WP is to provide upper bounds on stabilizing intertransmission intervals. As long as these intertransmission upper bounds are met, control systems are provably stable in same appropriate sense. In order to decrease conservativeness of these upper bounds, information received in the last transmission instant are utilized. In the literature, this paradigm is known as self-triggered exchange of information.

In addition, one may want to intentionally impose intermittent exchange of information on control systems. When information exchange is costly or undesirable (e.g., in scenarios where somebody could eavesdrop on our communication), it may be advantageous to decrease the rate at which the information is transmitted/exchanged. However, this decrease in the information exchange rate does not come for free. As the amount of exchanged information is reduced, the performance of the control system impairs. The rate of convergence drops causing the control report to increase (e.g., fuel consumption increases). In addition, the detrimental effect of propagation delays becomes more evident. Therefore, intentional intermittent feedback and its repercussions need to be investigated in more detail. To the best of our knowledge, to this date multi-UAV systems are limited to tactical surveillance and reconnaissance missions.

15. SUBJECT TERMS

EOARD, human-in-the-loop control, human machine interaction, multi-agent systems, decentralized control, supervised autonomy

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18, NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Kevin Bollino
UNCLAS	UNCLAS	UNCLAS	SAR	25	**19b. TELEPHONE NUMBER** *(Include area code)* +44 (0)1895 616163

Human-in-the-loop Control of Multi-agent Aerial Systems Under Intermittent Communication

(Grant Agreement:FA8655-13-1-3055)

FINAL REPORT 2013-2015

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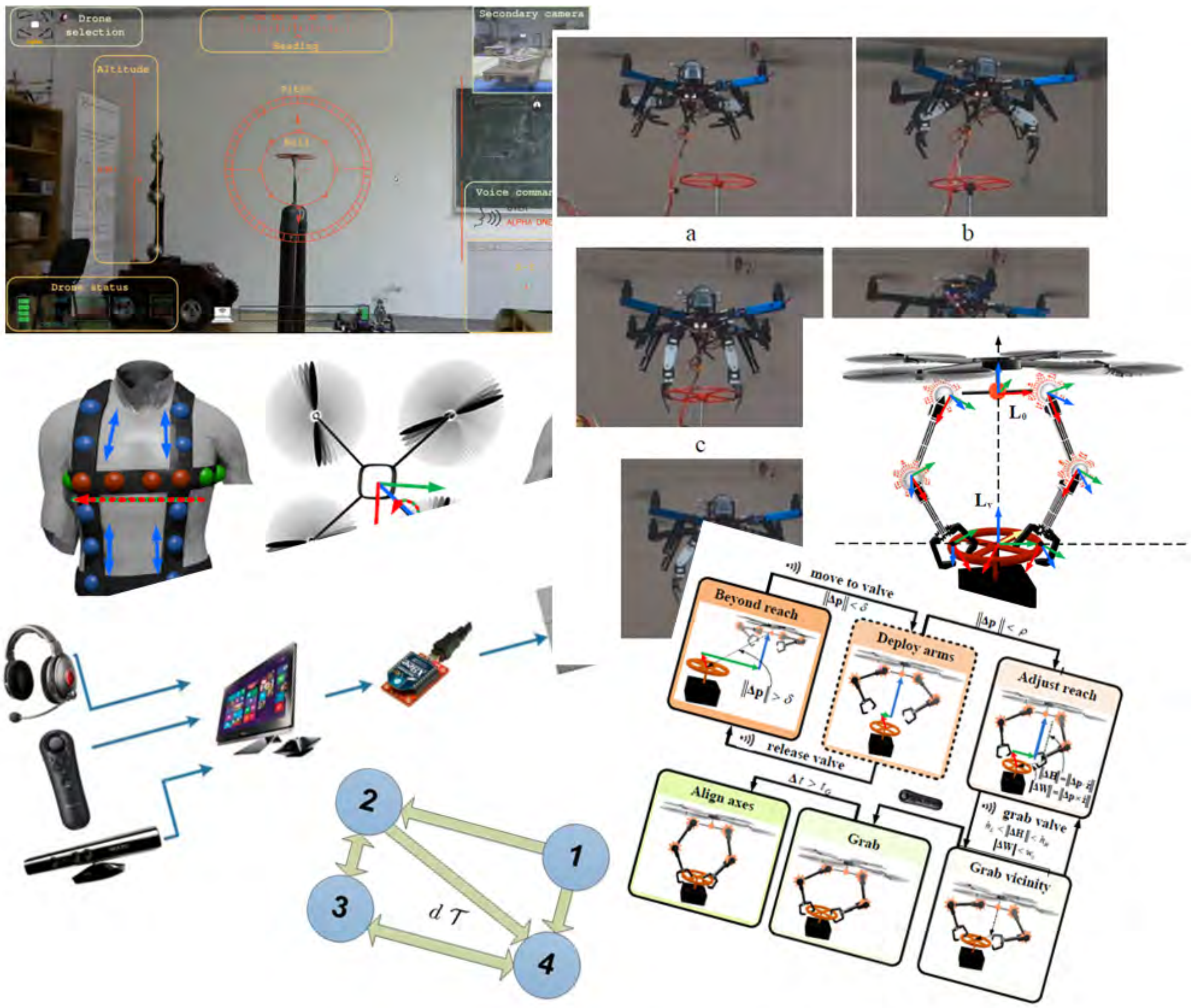

Introduction

This paper reports results of the project sponsored under grant agreement number FA8655-13-1-3055. Each work package is briefly disseminated separately, to show the overall progress of the project. We attach project related papers and reports to give a full and detailed picture of the work undertaken during the project. Also, video footage of conducted experiments and simulation analysis is added to complete the report. The report is organized as follows:

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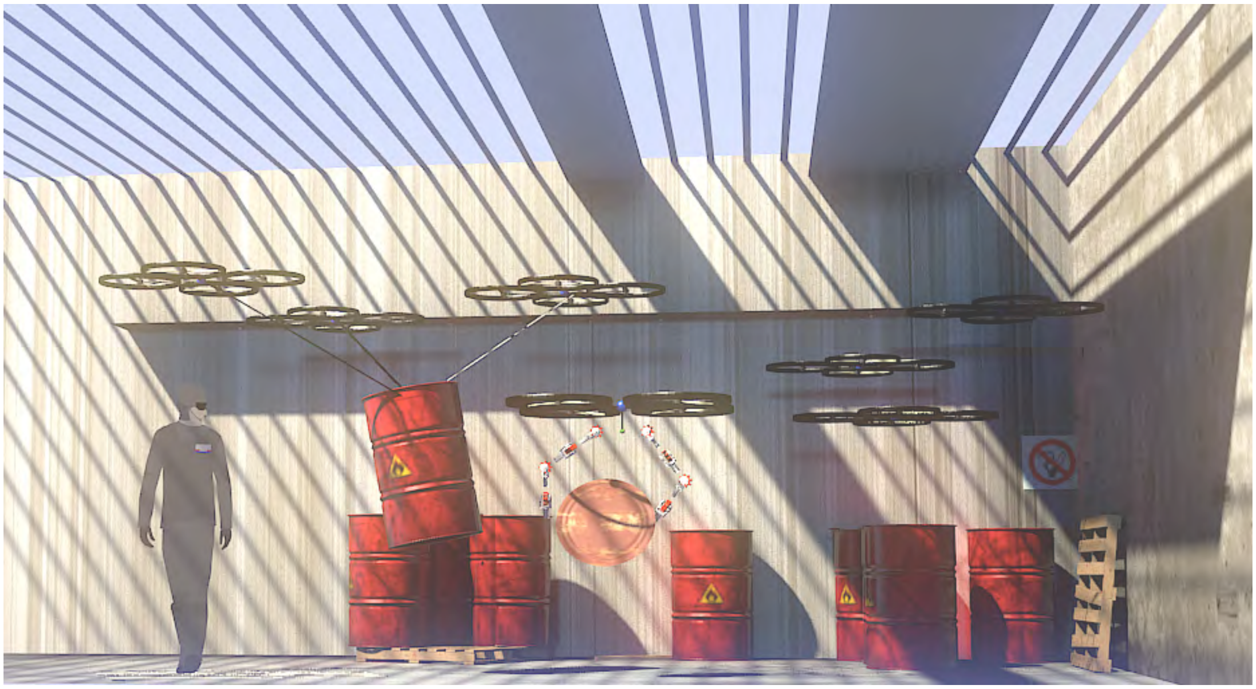
Additional material attached to the report:

- papers published under this grant
- papers written through this project still under review or yet to be published
- internal reports generated within the project
- videos showing recent experimental results

The following abbreviations are used: [WP = Work Package; T = Task; PM = Person month; M = Month; PI = Principal Investigator; PostDoc = Post Doctoral Associate; Grad = PhD Student; MS = Master Student]



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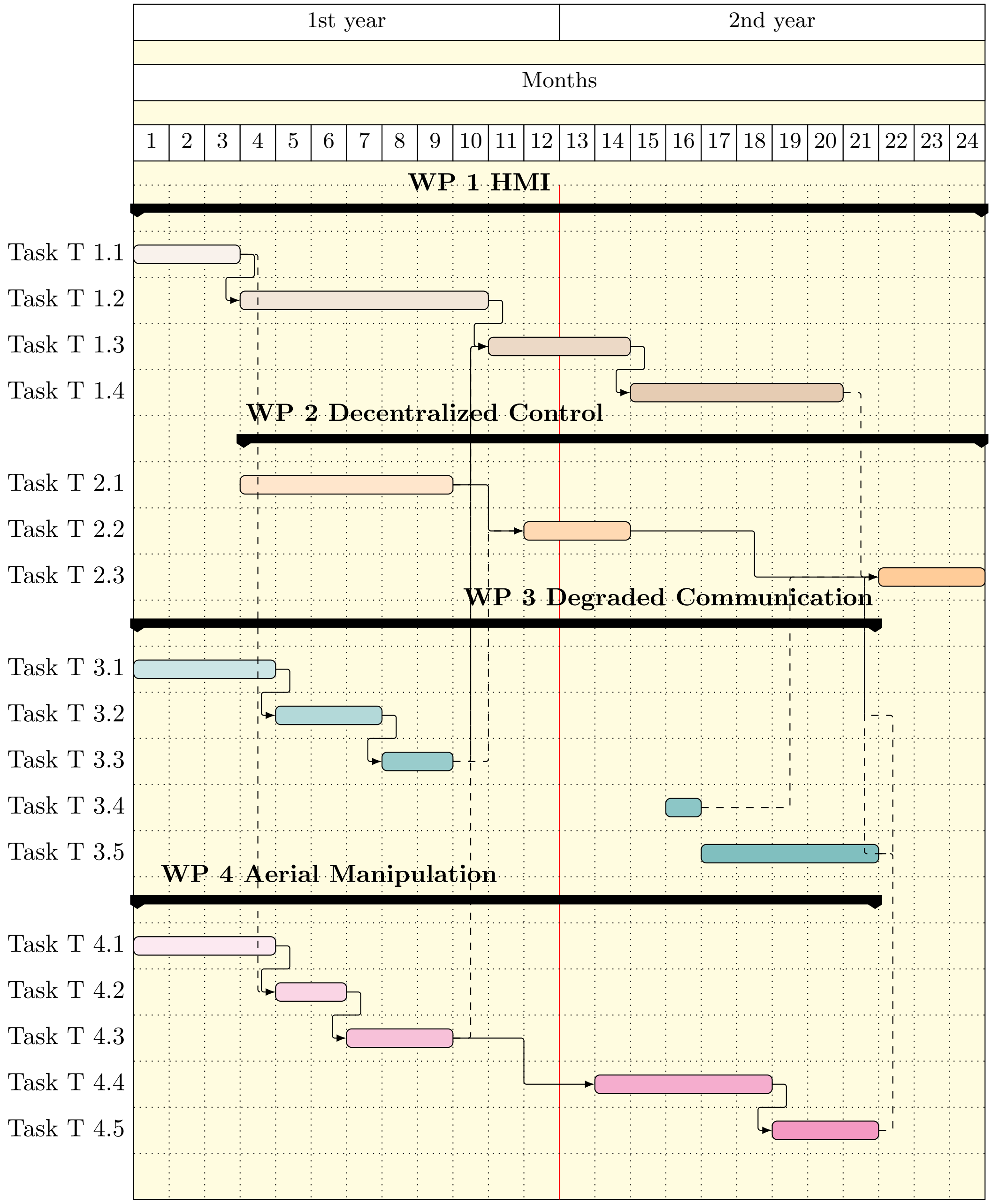
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Report

WP 1 Human Machine Interaction

Herein we present results in designing and defining novel human machine interaction based on psychological measures as well as multiple source control inputs, that utilize various communication channels.

T 1.1 HMI structure and design

[***Duration: M1-M3; PM: 2 PostDoc, 1 Grad, 3 MS, 1 PI; Dependency: none***]. In this task we define and systematically present the structure of the proposed HMI in the sense of required hardware and software. We investigated which types of devices are suitable for representation of information the human operator is getting from the agents in various missions and through various sensory channels (force-feedback, sounds, electric gloves, etc.). Results showed that target location cannot be suppressed by focusing visual attention. Even when visual attention was fully focused to a predefined target location, an auditory or visual cue coming from the opposite direction was still able to capture visual attention. It is our aim to make use of this automatic capture of attention phenomena. Key variables that need to be constantly available in flight operations need not interfere with a visual screen which enables visual search needed to perform the main task. Data can be see through during an operation, and capture attention only in key moments by making a prompt movement. Auditory information draw fastest reaction times (140-160 ms), followed by tactile information (155 ms) and visual information (180-200 ms) [30]. Studies also found that tactile cues can be even faster than other sensory channels, when used for alarms or direction cues (firing left, right, center) [31]. Because we deal with a lot of noise coming from UAVs during experiments, we focused on tactile information in order to translate information to the operator. Furthermore, results showed that speech input was significantly better than manual input in terms of task completion time, task accuracy, flight/navigation measures, and pilot ratings in a continuous flight/navigation control task [32]. Utilizing the advantages of each communication channel, we built the human machine interface in the following manner:

Control inputs:

- *joystick control* - was utilized using PlayStation3 Move Navigation Controller, which connects to the PC via bluetooth, thus allowing the operator to move freely.
- *voice control* - was based on CMU Sphinx Open Source Toolkit for Speech recognition wrapped in ROS, using a standard headset with a microphone
- *operator motion tracking* - was achieved with Openni tracker, a ROS based package for human pose detection via standard Microsoft Kinect RGBD sensor

Feedback outputs:

- *visual feedback* - The operator observers the mission status through cameras placed on specific UAVs. Visual display captures special focus and attention when emergency occurs
- *haptic information feedback* - We designed a custom haptic rumble array, that can be placed on specific points of the operator in order to pass the information about the UAS status.
- *auditory information feedback* - Standard headset can also be utilized to pass on emergency situation awareness to the operator.

We were able to design and build the entire human-to-machine portion of the HMI. We fused joystick, voice and motion tracking together to achieve a successful aerial manipulation task. We have also used this

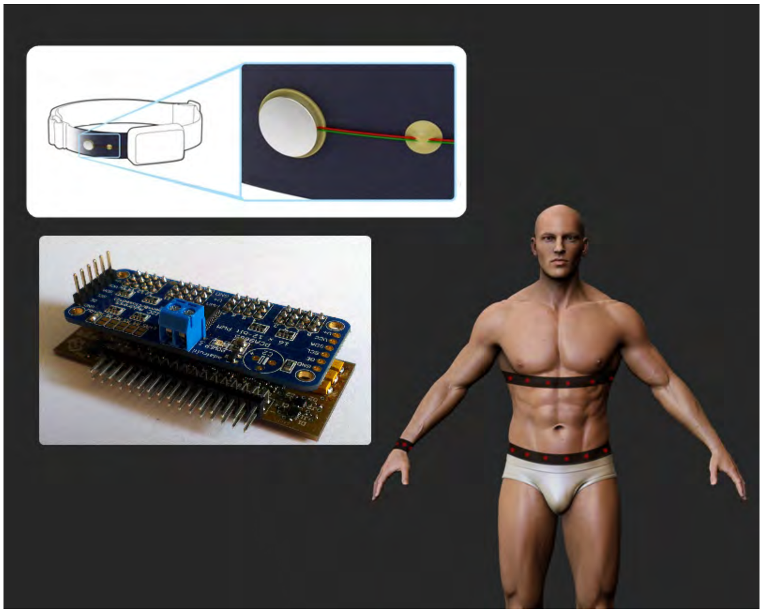

Figure 1: Vibration motor array

portion of the HMI to control a formation of UAVs in an indoor environment. The attached videos show the results of this fusion: [1–3]. Visual feedback was successfully verified in aerial manipulation experiments, while auditory feedback was used for emergency awareness. We have designed and developed the necessary hardware for the vibration motor array shown in Fig. 1. More details on the BOM and board layout, as well as images of the final product can be found in technical report [4]. The necessary interface was developed to connect it to the PC, via BeagleBone Black.

Another aspect of the task is to provide the HMI with information on the operator state (EKG, skin conductance, HR, breathing rate, etc.), thus allowing the system to autonomously override operator inputs if necessary. Low correlation among physiological measures suggests that different people in the same stressful situation may respond by changes in different measures, e.g. one athlete may display an elevated HR or its variability, whereas another athlete may show an increase in BP or EMG [5]. Along with objective measures of arousal (EEG, GSR, HR, BP, EMG), subjective measures, such as perceived heartbeat, a dry mouth, ”butterflies in the stomach”, cold and clammy hands, trembling muscles, sweating all over, and tension, characteristics of movements (smooth, easy, tight) and feeling thirst, hunger, cold, or pain (or painlessness), must also be taken into account when predicting performance. After analyzing all the possibilities, we collected the following objective measures:

- EEG helmet
- ECG, Hear Rate measure
- Galvanic skin response(GSR)
- Breathing rate

Besides afore mentioned physiological measures, we incorporated subjective measures such as hedonic tone, or perceived control and accuracy after every task, along with objective measures of success (performance score) into experiments. We collected this data of subjective measure of stress before and after each

Figure 2: Heterogeneous symbiotic robotic system deployed on a mission to close a valve in a disaster stricken industrial environment

experiment, in order to gain more insight into relations between biological measures and true state of stress. Through testing we collected biological stress related data while the operator was controlling multiple UAVs. More details can be found in [5].

Portions of this task are partly disseminated in [6].

T 1.2 Virtual environment development

[***Duration: M4-M10; PM: 3 PostDoc, 1 Grad, 7 MS; Dependency: Task T 1.1, Task T 2.1, Task T 3.1, Task T 4.1***]. In order to safely test the proposed controllers and human-machine interface, we developed a virtual environment based on Gazebo ROS simulator. Gazebo simulator was chosen because it is widely used in ROS community. In this environment we were able to implement and test the algorithms from WP 2, WP 3 and WP 4. Virtual environment was populated with custom designed UAV quadrotor and MMUAS quadrotor dynamic models, which were used for controller testing. For dynamic modelling we adapted the existing Hector Gazebo package, which implements quadrotor dynamics. The existing package simulates wind disturbances, propeller aerodynamics and body dynamics, and was adapted for the specific values of the quadrotors used in the project. This way, we can expect similar behavior in simulation as well as experimental analysis. We used the VE, to create a realistic stressful scenario to train the operator how to use the HMI for multi-agent control as well as to train the HMI to estimate the stress levels of the operator.

T 1.3 HMI and virtual environment (VE) integration

[***Duration: M11-M14; PM: 2 PostDoc, 1 Grad, 4 MS, 1 PI; Dependency: Task T 1.2***]. Given the underlining ROS environment being used in the development of the project, it becomes straightforward to switch between the virtual environment and the real system. All incorporated HMI elements are connected with the virtual environment. In the second part of the task we developed a scenario for training the operators and testing the proposed algorithms. The scenario story was based on an imagined event of an unexplained breakdown at local Nuclear Power Plant Krsko. The operator was required to land on a valve and close it in order to shut the power plant down (Fig. 2). A combination of point rewarding, complex cognitive tasks (Fig. 3) and limited time frame gave us the necessary psychological evaluation of the operator stress level . Results of this task were used in T 1.4.

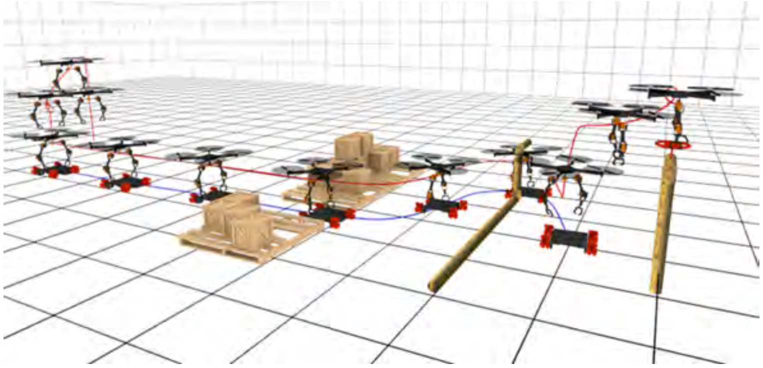

Figure 3: A task sequence in which the UGV carries the UAV up to the pipe, where the UAV lifts the UGV across the obstacle, lands, approaches the valve, takes off and closes the valve.

T 1.4 HMI and experimental multi-UAV system integration

[***Duration: M15-M20; PM: 2 PostDoc, 1 Grad, 4 MS, 1 PI; Dependency: Task T 1.3, Task T 2.2, Task T 4.5***]. Within this task we wrapped-up research done in WP1 and integrated a framework for human-in-the-loop control of multi-agent systems (MASs), comprised of different unmanned aerial vehicles (UAVs), under realistic communication channels (Fig. 4). Augmented human machine interface that fuses both classical wireless joystick control together with voice control and motion tracking is put in operation. The idea behind this implementation is to allow the operator to pass intuitive motion commands to an unmanned aerial vehicle via joystick and at the same time control the aerial robotic manipulator through arm motion, rather than elaborate joystick modes. Added voice control (Fig. 5) is ideal for single voice commands, which are particularly important when the robot is pushed towards the autonomous state. Furthermore, in the developed HMI sensors are mounted on the operator in order to allow monitoring of the operator psychological status. By having this information the proposed HMI is able to decide on the autonomy level of the system independently of the operator. This paradigm is known as the mixed-initiative adjustable autonomy (MIAA). The HMI has been tested in the experiments that involves autonomous valve turning operation [7], [8].

WP 2 Decentralized Control of Multi Agent Systems with HMI

T 2.1 Algorithms for Distributed Control of Multi UAV System

[***Duration: M4-M9; PM: 2 PostDoc, 4 MS; Dependency: none***]. Within this task we explore and develop a set of control algorithms for decentralized formation control of multi-agent systems. We consider a group of n agents designated to perform a certain mission. Their interactions and communications are represented through a graph $G_n = (\nu_n, \epsilon_n)$ where $\nu_n = [1, \ldots, n]$ is a set of vertices representing physical agents and $\epsilon_n = \{e_{ij}\}, i, j \in \nu_n$ is a set of edges representing local interaction and communication links between agents. First, a consensus based control algorithm is used for decentralized formation control [33] represented by

$$\dot{x}_i(t) = \sum_{j \in \mathcal{N}_i} [x_i(t) - x_j(t)], \quad \dot{x}(t) = -L(t)x(t)$$

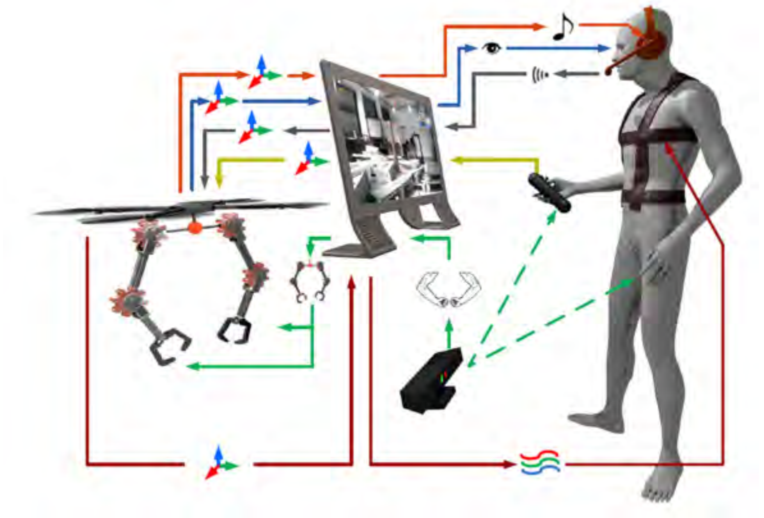

Figure 4: The structure of augmented Human-Machine-Interface

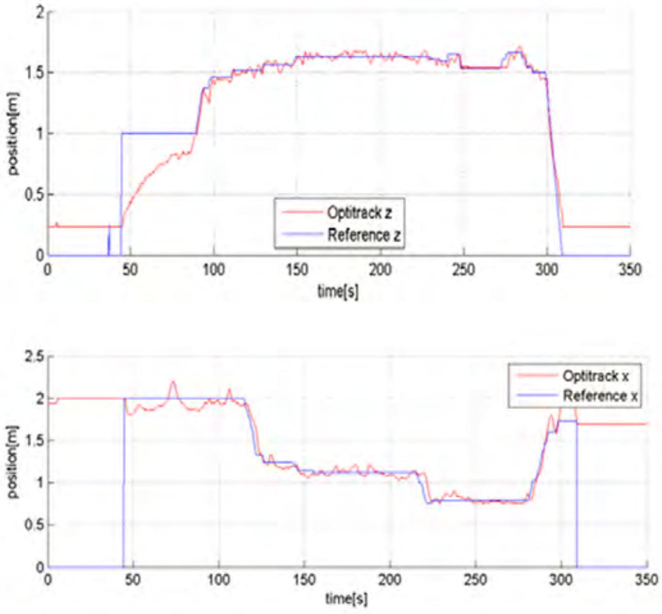

Figure 5: The platform position response on the voice command

where $x = [x_1 \dots x_n]^T$ is a vector of agents' states, $\mathcal{N}_i$ is the set representing neighboring agents and $L(t)$ is the Laplacian matrix of the graph G_n. Consensus is reached when

$$\forall x_i(0), x_j(0), i, j \in [1 \dots n] \quad \|x_i(t) - x_j(t)\| \to 0, \quad t \to \inf,$$

and if the graph G_n contains a spanning tree. In our application this means that agents' positions and their respective velocities will synchronize, i.e., they will reach the same value. Since we want the formation to track a certain trajectory in a decentralized way, we modify consensus based algorithm as

$$\dot{x}_i(t) = \sum_{j=1}^{N} a_{ij} \left[x_i(t) - x_j(t)\right] - \left[x_i(t) - x^*\right],$$

where a_{ij} is the element of the weighted adjacency matrix and x^* is the position of the each agent inside of the formation given in the moving formation frame. This form of consensus control algorithm is known as pinning control, and is proven to converge asymptotically if the graph G_n contains a spanning tree. Simulation results are provided in simulation video [9]. One of the pinning control drawbacks is that the convergence is asymptotic. Therefore we have implemented a binary consensus control algorithm given by

$$\dot{x}_i(t) = \sum_{j=1}^{N} a_{ij} \operatorname{sgn}\left(\left[x_i(t) - x_j(t)\right]\right) - \operatorname{sgn}\left(\left[x_i(t) - x^*\right]\right),$$

where by using sgn we are using only the sign of the relative position and velocities between the agents. Advantage of binary consensus based algorithm is its finite time convergence as proven in [34] and small local information message. On the other hand, the down side is that it is a bang-bang type of controller which can be aggressive on the actuators and overly sensitive on small changes of agents states. To overcome this, we introduced a dead zone in the algorithm to neglect small changes of the agent position and velocity. Simulation results are provided on [9].

As a third method for decentralized formation control we use and extended a technique developed in [35] based on potential field. In this approach attractive and repulsive forces are created by potential gradient of the same form. The goal is to move the agents from an initial formation position to a desired final position $Q = Q_{T|t\to\infty}$. Configuration space is symmetric due to the agent's conditional identity. If any two agents are swapped, the configuration space does not change. This can be described by the action of an idempotent discrete orthogonal group T whose elements $T(i,j)$ are replacing the configurations of the i^{th} and j^{th} agent. In that case, the elements $T(i,j)$ represent a $3N \times 3N$ matrix that changes the ordering of the i^{th} and j^{th} agent. The matrix $T(i,j)$ is given as

$$T(i,j)_{\alpha\beta} = \begin{cases} I_3 \text{ ; if } \alpha = \beta, \alpha \neq i \wedge \alpha \neq j \\ I_3 \text{ ; if } \{\alpha, \beta\} = \{i, j\} \\ 0 \text{ ; else} \end{cases} \tag{1}$$

Indices α and β denote quadratic blocks of the third order. Moreover, each of these quadratic blocks is a third order identity submatrix. The configuration space is not changed if the third order identity submatrices are located on the main diagonal of the $T(i,j)_{\alpha\beta}$ matrix than there is no change in the configuration area. Swapping of any two rows of the matrix $T(i,j)_{\alpha\beta}$ corresponds to the swapping of two agents in the configuration space. Due to a conditional identity of agents, the configuration space is symmetric and the agents could be distinguished only by their control parameters. Implementation wise, the initial state of the configuration space is irrelevant since the control parameters are assigned after the agent's initial positions are defined. The control law of a formation of agents is given by the equation

$$\ddot{q}_k + b\dot{q}_k + \frac{\partial U_k(q)}{\partial q_k} = 0, \quad b > 0, \quad \forall k \in \{1, ..., N\}, \tag{2}$$

where q are agent states, U_k is the control input from the potential function and $b > 0$ is the damping coefficient that makes the system dissipative. The potential function of an agent is defined as

$$U_k(q, q_T) = -\sum_{j \neq k} u_k(d_{kj}, \sigma_k) + \sum_{j} u_k(r_{kj}, \sigma_k), \tag{3}$$

where the elementary potential function

$$u_k(\rho, \sigma_k) = u_k\left(\frac{\rho^2}{\sigma_k}\right), \rho \in \mathbb{R}^3, \sigma_k \in \mathbb{R}^+$$

is in the form of a bell-shaped function, i.e. Gaussian function. Vector $\rho = r_{kj} = q_k - q_{Tj}$ represents the distance between the agent k and target j, and $\rho = d_{kj} = q_k - q_j$ is the distance between the agents k and j. Parameter $\sigma_k > 0$ is the control parameter which affects the position and existence of certain singularities. From the viewpoint of physics, the elementary potential function describes the interaction among the targets and agents, as well as the interaction among the agents themselves. Separately changing each agent's control parameter effectively changes the interaction range. This approach has been implemented in simulation and experimentally [10].

Considering the work done by prof. Lewis and his group on trust based control [36], we developed a mechanism for decentralized trust-based self-organizing cooperative control. The driving force of this work is the idea that not all agents are equally adept to take the role of the group leader at a given moment. Depending on the application, agents with the most desirable sensing, communication or processing capabilities should take the leading role. Hence, our main objective is to establish a group hierarchy in a decentralized fashion and reconfigure the underlying communication topology accordingly. The hierarchy is established upon trust values towards each agent in the group. These trust values reflect the reputation that each agent enjoys within the group. Initially, we construct observed trust values of each agent by exploiting its local observations and observations received from the neighbors. Next, these observed trust values are passed on to the mechanism that favors more accomplished agents by assigning those agents higher trust values. Since this mechanism is decentralized, scenarios with unequal trusts values toward an agent need to be handled with caution in order not to compromise the collective behavior. To that end, we employ adaptive control concepts when negotiating trust values. The proposed mechanism is illustrated through a decentralized formation control case study. In extension, we present a formal proof of convergence of the proposed adaptive mechanism for the network topologies that can be represented with directed weighted graphs. The proposed mechanism is illustrated through a case study of decentralized formation control of autonomous agents. We provide an in-depth analysis of several possible scenarios regarding the proposed control structure. The results of this task were disseminated within following papers [11–13]. Simulation and experimental results can be seen in following videos [9, 14, 15].

T 2.2 Distributed Control of Multi UAV System with Realistic Communications Channels

[***Duration: M12-M14; 1 PostDoc, 2 MS; Dependency: Task T 2.1, Task T 3.1, Task T 3.2, Task T 3.3***] The main contributions of the research undertaken within this task are threefold. First, our analysis applies to MASs with general heterogeneous continuous-time linear agents (not merely to single- or double-integrator dynamics) with exogenous disturbances, directed communication topologies and output feedback. So far researchers consider passive agents without external disturbances and balanced topologies, not dealing with transmission rates, directed graphs nor output feedback. We do not impose specific requirements on the agent and controller dynamics per se nor on the underlying communication topology. Basically, when given local controllers do not yield Lp-stability (with respect to a set) of the nominal system, one can seek for another topology or design alternative controllers. Second, when communication delays are greater than the sampling period, no other MAS work takes into account the concurrent adverse effects

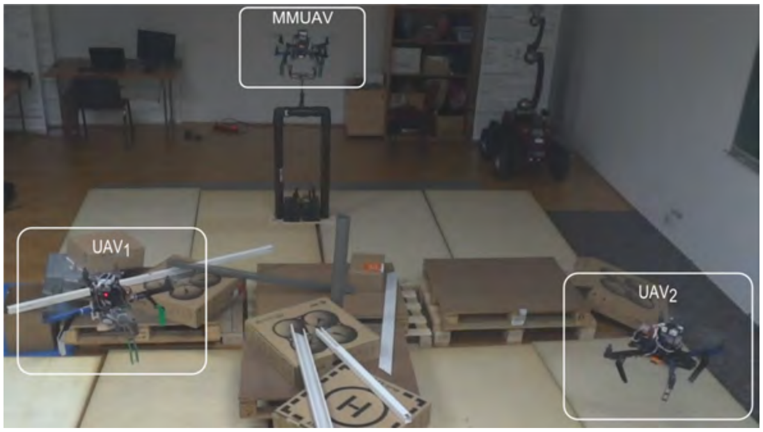

Figure 6: The final experimental scenario of the project.

of all aforementioned realistic data exchange phenomena. Third, the obtained transmission intervals are confirmed experimentally. For plant-controller settings, comprehensive theoretical and experimental studies of degraded communication environments are reported, however, imposed Zero-Order-Hold (ZOH) sampling do not consider noisy data nor scheduling protocols and disturbances. The results were disseminated in paper [16]. Furthermore, within this task we experimentally validated earlier developed multi-agent formation control based on potential functions [13]. Video clips are available at [10, 17].

T 2.3 Human-in-the-loop Control of Multi-agent Aerial System under Intermittent Communication - Experimental Validation

[***Duration: M22-M24; PM: 2 PostDoc, 1 Grad, 3 MS, 1 PI; Dependency: WP WP 1, WP WP 4, WP WP 3, Task T 2.2***]

In this task we made the final, experimental, validation of a framework for human-in-the loop control of multi-agent systems, composed of several types of UAVs, with realistic communication channels that give rise to intermittent, noisy and delayed information. As a part of this framework, we proposed a novel design of an HMI that allows a human to become a supervisor, when necessary, instead of a single unit operator. Furthermore, the proposed framework allows the supervisor to interact with its surroundings by deploying a dexterous aerial robot as a component of multi-agent systems. Finally, we determined stability conditions for multi-agent aerial system control under decentralized approach in degraded communication environments. A scenario (Fig. 6), displaying salient features of this framework, brings together a heterogeneous team of aerial robots, each with its particular capabilities, and a human operator in order to close a valve in a disaster stricken industrial environment. Experimental results, presented in [7], verify functionality of the proposed framework. Video clip is available at [18].

WP 3 Degraded Communication Environments

This work package is dedicated to robustness analyses of control systems (designed in other WPs) with respect to realistic communication network artifacts. Under the term realistic network artifacts, we refer to communication channels that distort exchanged information and introduce propagation delays, packet dropouts/collisions, limited network throughput and communication range. The main goal of this WP is to provide upper bounds on stabilizing intertransmission intervals. As long as these intertransmission upper bounds are met, control systems are provably stable in same appropriate sense. In order to decrease conservativeness of these upper bounds, information received in the last transmission instant are utilized. In the literature, this paradigm is known as self-triggered exchange of information [37, 38].

In addition, one may want to intentionally impose intermittent exchange of information on control systems. For example, when information exchange is costly or undesirable (e.g., in scenarios where somebody could eavesdrop on our communication), it may be advantageous to decrease the rate at which the information is transmitted/exchanged. However, this decrease in the information exchange rate does not come for free. As the amount of exchanged information is reduced, the performance of the control system impairs. For instance, the rate of convergence drops causing the control effort to increase (e.g., fuel consumption increases). In addition, the detrimental effect of propagation delays becomes more evident. Therefore, intentional intermittent feedback and its repercussions need to be investigated in more detail.

T 3.1 Enhancing our previous work with the ability to account for propagation delays

[Duration: M1-M4; PM: 2 PostDoc, 2 MS; Dependency: None] The research carried out within T 3.1 proposes a methodology for computing Maximally Allowable Transfer Intervals (MATIs) that provably stabilize nonlinear Networked Control Systems (NCSs) in the presence of disturbances and signal delays. Accordingly, given a desired level of system performance (in terms of $\mathcal{L}_p$-gains), quantitative MATI vs. delay trade-offs are obtained. By combining impulsive delayed system modeling with Lyapunov-Razumikhin type of arguments, we are able to consider even the so-called large delays. Namely, the computed MATIs can be smaller than delays existent in NCSs. In addition, our stability results are provided for the class of Uniformly Globally Exponentially Stable (UGES) scheduling protocols. The well-known Round Robin (RR) and Transmit-Once-Discard (TOD) protocols are examples of UGES protocols. Apart from the inclusion of large delays, another salient feature of our methodology is the consideration of corrupted data. To that end, we propose the notion of $\mathcal{L}_p$-stability with bias. We applyed the proposed methodology to the control laws developed in WP 1 and WP 4 as well as to the decentralized formation control mechanisms and agent models developed in WP 2. Presumably, we focused mainly on linear control laws and models because our methodology is robust against modeling uncertainties. In addition, the linear setting is more suitable from the viewpoint of T 3.2. Afterwards, the obtained results were verified experimentally by using the testbed and modeling developed in WP 1, WP 2 and WP 4. The results of this task are disseminated in [19].

T 3.2 Consideration of control systems with zero eigenvalues

[Duration: M5-M7; PM: 2 PostDoc, 1 MS; Dependency: Task T 3.1] Within the research conducted regarding T 3.2, we formulate and study the concept of $\mathcal{L}_p$-stability with respect to a set. This robustness concept generalizes the standard $\mathcal{L}_p$-stability notion towards control systems designed to steer the system state into the vicinity of a set rather than of a point. We focus on stable LTI systems with the property that all eigenvalues with zero real part are located in the origin. Employing the Real Jordan Form, we devise a mechanism for computing upper bounds associated with $\mathcal{L}_p$-stability and $\mathcal{L}_p$ to $\mathcal{L}_p$ detectability with respect to the equilibrium manifold. Notable examples of this class of LTI systems arise from consensus control. In a self-triggered realization of consensus control problems, each agent broadcasts its state only when necessary in order to achieve consensus. Consequently, the control signal of each agent is updated based on currently available (but outdated) information received from the neighbors. Bringing together $\mathcal{L}_p$-stability with respect to the consensus manifold and the small-gain theorem, we develop self-triggering for single-integrator consensus with fixed and switching network topology. In addition, we show that this consensus problem is Input-to-State Stable with respect to the consensus manifold. Finally, our results are corroborated by numerical simulations. Notice that, from the theoretical viewpoint, delays from T 3.1 are incorporated into T 3.2, which was straightforward duty due to generality of the methods devised within T 3.1 and T 3.2. The results of this task are disseminated in [20].

T 3.3 Investigation of model-based control and control signals with saturation

[Duration: M8-M9; PM: 1 PostDoc, 1 MS; Dependency: Task T 3.2] Model-based control/estimation and its advantages towards extending maximally allowable transfer intervals are reported in [1]. Basically, model-based control/estimation outperforms the common Zero-Order-Hold (ZOH) estimation strategy. Furthermore, our framework is readily applicable to models with saturation. In other words, the computed transmission intervals hold as well when saturation is considered, but result in local stability. In addition, saturation leads to globally Lipschitz dynamics, which we find not interesting enough to pursue further from the theoretical viewpoint. Experimental verifications of obtained transmission intervals for systems with saturation are reported in [16] and [7].

T 3.4 Making a stronger connection between $\mathcal{L}_p$- and Input-to-State stability

[Duration: M16; PM: 1 PostDoc; Dependency: None]

The performance trade-offs in multi-agent systems are posed as a dynamic programming problem and Approximate Dynamic Programming is employed to obtain (sub)optimal transmission intervals in [21]. The theoretical results from [21] are yet to be experimentally verified. A different viewpoint towards such performance trade-offs is taken in [22]. The work disseminated in [22] is both theoretical and experimental.

T 3.5 Consideration of performance trade-offs due to intermittent feedback

[Duration: M17-M21; PM: 2 PostDoc; 2 MS; Dependency: None] As in all previous tasks, our goal in T 3.1 is to reduce requirements posed on resources of Multi-Agent Networks (MANs) without compromising objectives of the MANs. Scenarios, in which agents of one network are required to maintain certain common knowledge, call for the study of consensus-seeking methodologies. In order to preserve this common knowledge in an uncertain and noisy setting and to detect changes in the communication topology, agents have to exchange information. Because each transmission and reception of information necessitates energy, it is desirable to rationally manage available resources in order to prolong the mission. Namely, communication should be induced only when consensus can no longer be guaranteed. In the remaining time intervals, the resources are released and cleared for other activities such as inter-network collaboration. To that end, we propose a parsimonious consensus-seeking mechanism which draws upon ideas of self-triggered communication. The proposed mechanism is inspected both theoretically and experimentally for performance vs. lifetime trade-offs using off-the-shelf wireless sensor platforms. The results of this task are disseminated in [23].

WP 4 Aerial manipulation

To the best of our knowledge, to this date multi-UAV systems are limited to tactical surveillance and reconnaissance missions. Equipping several agents with dexterous manipulators gives the multi-agent system the additional ability to interact with the environment. Within this work package, we completed most of the planned tasks, including: simulation, design, stability analysis and, finally, assembly and experimental testing of the manipulator arms.

T 4.1 Multi DOF manipulator design and construction

[Duration: M1-M4; PM: 2 Grad, 2 MS; Dependency: None] Within this task, we proposed, designed, constructed and tested several multiple Degree of Freedom (DOF) manipulators. After mathematical verification and consistency check, manipulator links were printed using a 3D printer, and manipulator arms were assembled. The material used in the printing process was Poly-lactic acid (PLA), which is a biodegradable polymer that can be produced from lactic acid, obtained from fermented crops. PLA requires

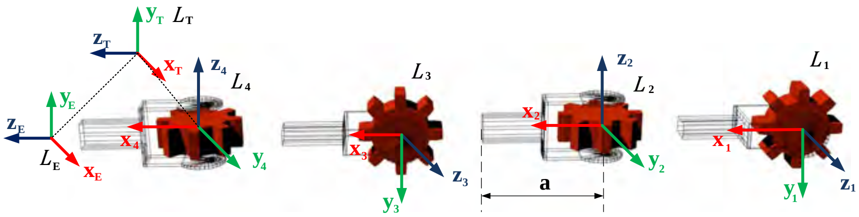

Figure 7: Reference frames for manipulator arms. See Fig 8 for detail on overall UAV-manipulator system

lower temperatures and giving stronger, more hard-wearing products, which makes it a good choice for the proposed construction.

The proposed mobile manipulating unmanned aerial system, featuring a quadrotor UAV and two 4 DOF manipulators, is shown in Fig 8. Using the recursive Newton-Euler approach and Denavit-Hartenberg parametrization for forward kinematics, each arm is modeled as a serial chain RRRR manipulator (Fig. 7) [39]. The connection between the quadrotor body frame and the first joint of each arm is represented with static revolute joint with a constant angular offset for each MM-UAV arm (Link B-0). Denavit-Hartenberg (DH) parameters of the manipulator arms shown in Fig 7 are given in Table 1, and Fig 8 depicts the overall UAV-manipulator system. Parameters θ, d, a, and α are in standard DH convention and q_i^1, q_i^2, q_i^3, and q_i^4 are joint variables of each manipulator arm $i = [A, B]$. Since the whole aircraft is symmetrical, the general kinematic structure is identical for the right and left arms, the coordinate frames are the same for each arm, and only the link B-0 is different for the two arms. Reference frames are shown in Fig. 7 which relate the fist joint L_1 to the end effector frame E. To make the DH parameters consistent, an additional, virtual frame L_T is set in the origin of frame L_4.

With Denavit-Hartenberg parametrization, joint frames are set and direct kinematic equations for each serial chain are derived. This procedure is repeated for both manipulator arms. Individual links that form the arm are consistent in size, mass and shape (i.e. their mass m_L, kinematic parameter a and tensor of inertia J_L are identical).

Valve, knob, and handle turning has been widely studied for use with industrial robots, mobile manipulators, and personal assistance robots. A typical requirement involves a grasp and turn of an object that remains fixed to the environment but allowed to rotate. Our framework and solution will be evaluated by performing valve turning, which is one of the tasks required for the recent DARPA Robotics Challenge (DRC) [40]. The task requires a robot to locate, approach, grasp, and turn an industrial valve with two hands. Valve turning presents a challenging test-case for any system due to the perception and dexterous manipulation required [41]. Because previously mentioned 4 DOF arms lack the necessary payload the carry the entire weight of the UAS, we redesigned the manipulator system using dynamixel servo controllers [6]. The increase in mass was compensated with less degrees of freedom, yielding a 2 DOF, dual arm manipulator with somewhat simpler DH Table 1.

Link	θ	d	a	α
1	$q_A^1 - \frac{\pi}{2}$	0	3.75	$-\frac{\pi}{2}$
2	q_A^2	0	3.75	$\frac{\pi}{2}$
3	q_A^3	0	3.75	$-\frac{\pi}{2}$
4	$q_A^4 + \frac{\pi}{2}$	0	0	$\frac{\pi}{2}$
T-E	0	0	3.75	0

Table 1: Denavit-Hartenberg Parameters for Manipulators $[cm]$. Showing Arm A only for clarity.

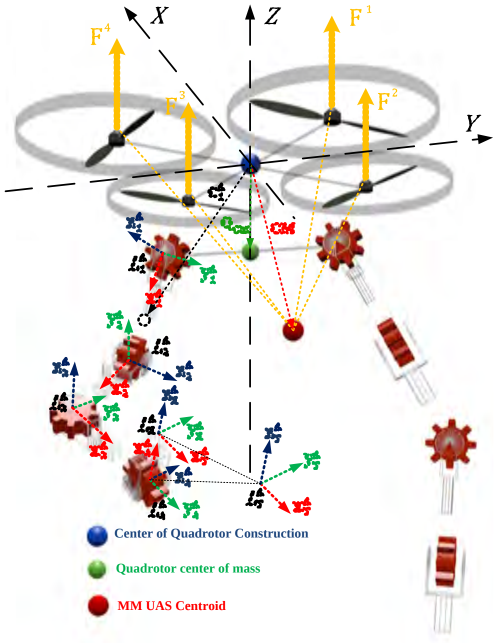

Figure 8: Complete model of the Mobile Manipulating Unmanned Aerial System

Table 2: Denavit-Hartenberg Parameters for Manipulator

Link Number	θ (rad.)	d (mm)	a (mm)	α (rad.)
1	q_1	0	L_1	0
2	q_2	0	L_2	0

With the two proposed designs we were able to evaluate different manipulating tasks like: pick-and-place, peg-in-hole or valve/knob turning, which completes the work planned within this task. The results of this task were disseminated within the following papers: [6, 24–26]

T 4.2 Multi DOF manipulator control

[Duration: M5-M6; PM: 1 Grad, 2 MS; Dependency: Task T 4.1, T 1.1] Hardware and software infrastructure for the control of manipulator arms is built to comply with the proposed HMI design. Entire control infrastructure is built upon Robot Operating System (ROS), so that the control inputs and feedback from the manipulator can be easily past between the system and the operator through the HMI. Using ROS allowed us to easily switch between the simulations and the real implementation. Since there are two distinct manipulator implementation, each based on different hardware, two low-level controllers were utilized. Flyduino servo controller was used to control the 4 DOF manipulators, where arm consists of a servo powered rotation joint, and a DC powered linear actuator controlling the extension of the arms. This is an Arduino based hardware, which we were able to incorporate into ROS through serial RS232 based protocol.

2 DOF manipulator arms are powered with Dynamixel AX-12 servo controllers, that have significantly bigger payload capabilities but weigh a lot more then standard servo motors used in 4 DOF arms. AX-12 servo motors come with a low level controller built in the system, and use a specific USB2Dynamixel controller to connect with PC. Transport layer based on USB protocol is wrapped as a ROS interface, and makes it possible to connect both manipulator setups to the same HMI.

Finally, the interface between the operator and the manipulators is achieved through motion sensing using standard Kinect sensor. Through interpretation of human poses and motion, we are able to map the human moves into manipulator pose control inputs. This allowed a natural and intuitive control of the arms, while performing various manipulation tasks.

T 4.3 Mobile Manipulating Aerial Vehicle mathematical model

[Duration: M7-M9; PM: 2 Grad; Dependency: Task T 4.2] The end goal of the mathematical model is to combine both manipulator dynamics and the dynamics of the quadrotor. Due to the resulting complexity of the model and keeping in mind specific mission requirements, the quadrotor dynamics considered in this paper do not account for various aerodynamic effects (i.e. blade flapping, ground effect, etc.) experienced during highly dynamic flying maneuvers. Most of the missions that include some form of interaction with the environment require stable hovering maneuvers, which justify a simplified mathematical model without accounting for the previously mentioned aerodynamic effects.

As the manipulator dynamics are introduced through the recursive Newton-Euler method, it is possible to separately model the quadrotor motion based on Newton-Euler equations for rigid body translation and rotation [42]. The two models are then combined to yield a complete model of the proposed mobile manipulating unmanned aerial system. The resulting equation is highly nonlinear. Previous work in this field has concentrated only on load mass stability problem, ignoring the coupled manipulator dynamics [43], [44]. For a 1 DOF gripper tools, this assumption is welcome, but for 4-DOF arms that introduce a significant increase in payload and moment of inertia this simplification cannot be applied. Two underlying effects are identified to directly influence quadrotor control are the change in the overall center of mass $\vec{CM}$ and moment of inertia $\mathbf{J}$. Building upon the results from [45, 46] we present a complete mathematical model to establish a stability criteria for this mobile manipulating unmanned aerial system [24].

T 4.4 Mobile Manipulating Aerial Vehicle control

[Duration: M14-M18; PM: 3 Grad, 2 MS, 1 PI; Dependency: Task T 4.3] This task is tightly coupled with the development of HMI. The teleoperation part of the controller was successfully implemented and tested in three benchmark manipulation tasks. The controller is devised based on the nonlinear dynamic model of the system, where we identified four parameters in the attitude control loop of UAV that change during flight and manipulation:

- K_m - Propulsion system gain changes drastically through time, especially in load manipulation missions.
- T_m - Propulsion system dynamics changes due to various effects as the mission progresses through time.
- β - The aerodynamic conditions constantly change during the flight.
- J - Moment of inertia changes depending on the load and manipulator pose.

Aerial manipulation missions mostly require steady flight conditions, for which the changes in the aerodynamic conditions as well as the aerodynamic coefficient β can be neglected. On the other hand, if the battery power supply is kept constant throughout the mission, the variations in the T_m can be minimized. The two remaining parameters, J and K_m diverge the most during aerial manipulation. The variations in the moment of inertia have been previously discussed. The propulsion system gain changes are mostly caused from the variations in the load mass, which changes the piecewise linearization of the quadratic relationship between the propeller thrust and the applied voltage. Apart from that, the variations in temperature and the battery depletion also change the linearized motor gain throughout the mission. In order to adapt to parameter changes, we implemented and tested adaptive control both in simulation and real system. Opposite from our expectations, once properly tuned, the system proved to be stable even without the adaptive control. In situations where the parameter changes cannot be predicted, we proposed and tested a model reference adaptive controller (MRAC). Using the Lyapunov stability theory, the controller is proven to be stable. The simulation results proved that the MRAC is capable of stabilizing the oscillations produced from the unstable PID attitude control loop.

To better utilize the MRAC and Gain Scheduling adaptive capabilities, a hybrid system based on a switching automaton was proposed. The hybrid system defines four phases of aerial manipulation missions: Flight phase, Arm Deployment phase, Manipulation phase and Adaptation phase. The system starts in the flight phase, where the MM-UAV flies to the designated point. During arm deployment, gain scheduling algorithm is crucial for keeping the system stable. After the arms are deployed, the UAV switches to the adaptation phase and starts the self induced oscillations in order to fine tune the controller using model reference adaptation. During the manipulation phase, the shift in the center of mass or the change of moment of inertia produced from interaction with the environment or from picking up an object, could drive the vehicle unstable. Therefore, the vehicle is allowed to switch back to Adaptation phase if such a problem occurs. After successfully picking up an object and before flying back to the base, the air robot once again changes to the Adaptation phase, before flying off. Once tuning is complete, the aircraft switches back to flight phase and flies back to the base. More details about the gain scheduling and model reference controller, as well as the automaton can be found in [24, 25, 27].

T 4.5 Mobile Manipulating Aerial Vehicle experimental verification

[Duration: M19-M21; PM: 1 Grad, 2 MS, 1 PI; Dependency: Task T 4.4]

The proposed controllers and HMI have been tested throughout experiments with the unmanned aerial system. The experiments conducted within this task proved the validity of the proposed aerial robots. We have selected three benchmark manipulation task, to verify the feasibility of aerial robot concept. The three chosen tasks are: Peg-in-hole, pick-and-place, and valve turning. These tasks exhibit various aspects of aerial manipulation problems. For instance, during peg-hole-task precise navigation is required in order to complete the mission safely. Unlike valve turning, during peg-in-hole, there is no full contact with the environment. Therefore, we use valve turning scenario to verify problems arising from full system contact with the environment. During pick-and-place there is an obvious discrete change in the dynamics of the aircraft (i.e. abrupt change in mass and moment of inertia due to payload increase) that the controller needs to compensate. Proving that the controller works for all three cases, we have verified the proposed concept. Another experimental verification within this task was to analyze the proposed HMI. We have conducted a series of experiments that showed that the multi-channel human machine interface alleviates the operator burden and allows him to complete the mission safely and efficiently, which is in part disseminated in [6]. Furthermore, we are attaching the following videos to show the experimental results: [28, 29]

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