Collaborative transportation with a team of rotorcraft

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***Abstract*— In this abstract, we present the preliminary work of a robust motion formation control system for a team of rotorcraft, which can be applied for tasks such as the collaborative transportation of heavy objects. The primary responsibility for the team is to form a geometric shape, which can be freely translated and rotated at the same time. This approach makes the robots behave as a cohesive whole in a predictive way, such that the team can be operated by a human as a single *rigid object*. The control system is the result of putting together Incremental Nonlinear Dynamic Inversion (INDI) and a *mismatched* gradient-based formation control, where the former algorithm tracks the desired accelerations provided by the latter. The robustness of the algorithm relies on the fact that it only demands local measurements from the robots, and that the rotorcraft do not need to exchange any information with each other. This makes the system suitable for deployment in environments where external localization resources are not available. Because of the low computational cost of the algorithm, it is possible to execute the control on a standard microcontroller. Consequently, the algorithm has a little impact on systems where low power consumption is a requirement. We present preliminary results, where an operator can command the group motion of a team of four rotorcraft, lifting an object that cannot be carried by a single vehicle.**

I. INTRODUCTION

Scientists and engineers have found in the multirotor a mechanically simple and inexpensive vehicle that can carry a broad class of payloads. As technology is progressing, the possibility of scaling these vehicles down makes all the logistics associated with them even easier. Therefore, different collaborative tasks with teams of small rotorcraft become feasible. In particular, central to the robotics community is the replacement of individual and independent robots executing repetitive tasks by the exploitation of teams of co-operative robots solving multiple tasks together. The usage of robots in a coordinated fashion is already a reality in many tasks such as the transportation of objects [1], area exploration, and environmental surveillance [2]. Difficulties arise, however, when an attempt is made to implement fundamental control methodologies in actual robots. For example, recent works demonstrate multi-robot algorithms while they exploit external motion capture systems, not only as a ground truth, in order to perform multi-robotic tasks [3], [4], [5]. While these systems have advantages for rapid prototyping in a controlled environment, they present potential problems if one wants to scale up the multi-robot system or to make it independent of the environment.

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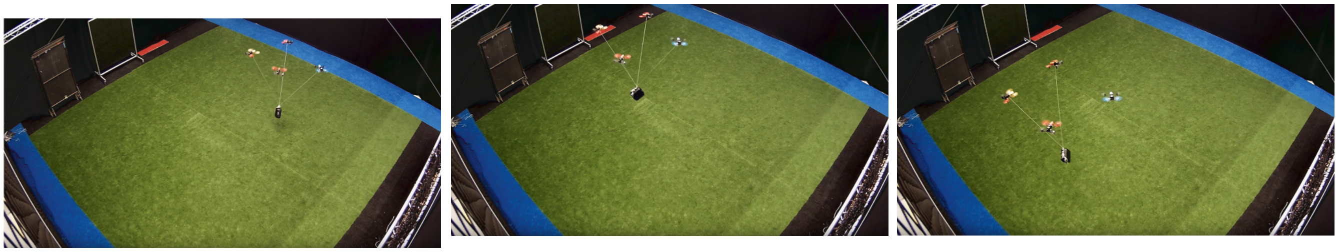
We present in this paper a motion formation control system for a team of rotorcraft, where the vehicles only rely on local information, i.e., relative positions with respect to their neighbors. We show that the system is suitable for the collaborative transportation of heavy objects, which a single vehicle is not able to lift by itself. While in our preliminary results we employed a visual tracking system, absolute positions or trajectory tracking are not used at all. In particular, our preliminary results show that the rotorcraft only need to know their local information at the relatively low frequency of 4 Hz, and the accuracy in the relative positions is in the order of the centimeters. Therefore, the experimental data suggest that current on-board technology for the measurement of inter-vehicle positions will not have a significant impact on the presented results of this abstract.

The abstract is organized as follows. In Section II we introduce Incremental Nonlinear Dynamic Inversion (INDI) employed in the rotorcraft, which is the algorithm responsible for tracking the acceleration signals given by the *mismatched* formation control explained in Section III. We finally present our preliminary experiments in Section IV and some conclusions in Section V.

II. INDI CONTROLLER

Incremental Nonlinear Dynamic Inversion (INDI) can be applied to the control of angular accelerations [6], and the control of linear accelerations in a cascaded way [7]. Most relevant for this research is the control of linear accelerations with INDI. The concept is that the desired attitude and the thrust are not calculated from a model each time the controller runs, but that they are *incremented* based on desired changes in acceleration. Disturbances, together with the forces from the actuators, are measured by the accelerometer on board. Therefore, the desired acceleration can be rapidly achieved by incrementing the previous control inputs, based on the difference between desired and measured acceleration.

The INDI can be compared to the integrator part of a PID controller, but while an integrator is blindly adding input, INDI takes the actuator effectiveness, actuator dynamics and filtering into account. Therefore, the INDI controller can precisely determine the size of the input increment that should be applied, and it knows when the output should be expected. Consequently, the controller reacts very fast to compensate even the strongest of disturbances, while tracking a rapidly changing desired acceleration signal. This strategy enables the team of rotorcraft to track the desired acceleration signal from the formation controller, regardless of the rope tension from external loads attached to the vehicles.



(a) Initial take off ($t = 0$).

(b) Scaling the formation for adjusting the tension from the ropes ($t = 30$).

(c) Flying around following the commands from an external operator ($t = 50$).

Fig. 1: Captions of the rotorcraft formation transporting an object. The video of this experiment can be watch at https://www.youtube.com/watch?v=HUZH46Oxc5c .

III. Formation control

The algorithm that stabilizes the desired shape and motion of the team is based on the novel concept of *mismatched* control [8]. This algorithm is an extension to the popular gradient-descent based strategy where the vehicles minimize error distances in order to form the desired shape. The motion of the team is achieved by introducing mismatches in the desired distances to neighboring rotorcraft. Therefore, neighboring robots disagree about the distance to be controlled. In particular, special sets of disagreements generate accelerations signals such that translational and rotational motions can be superposed, while the acceleration signals that controls the desired shape (without disagreements) are not compromised. The distance error signals are shown to be exponentially stable under this control strategy. Therefore, specific bounds to allowed disturbances can be given. For example, the controller will be robust against the tension from a rope in the collaborative transportation of an object.

IV. Experiments

We demonstrate a team of four rotorcraft Bebops from Parrot, with a heavy load attached to the four of them, which is too heavy for a single vehicle to lift. The video from this experiment can be watched at https://www.youtube.com/watch?v=HUZH46Oxc5c . The rotorcraft are running the Paparazzi open source autopilot, in which the proposed control system is implemented, i.e., the cascade control of INDI and the mismatched formation control. In fact, the code for the presented experiment is available and ready to use for the general public in the master branch of Paparazzi [9]. The system only needs the relative positions between some of the rotorcraft, and the action of an operator with a joystick controls the scale of the shape, as well as the rotational and translational of the desired *rigid shape*. In particular, each value of the joystick corresponds to a disagreement in the mismatched formation controller. A ground control station gathers the relative positions from a motion capture system and the commands from the joystick. The ground control station then calculates the desired acceleration signals and sends them to the corresponding rotorcraft. This preliminary test is done centralized and with a motion capture system. Nevertheless, the frequency of the algorithm runs at 4 Hz, and the relative positions have an accuracy of the order of centimeters. These facts, together with the inexpensive computational cost of the formation control (consisting of a couple of algebraic operations), suggest that with the currently existing technology, the same results can be reproduced in a fully distributed way without any external localization system.

V. Conclusions

We have shown preliminary results for collaborative transportation by a team of rotorcraft based on the theoretical results in [8] in combination with INDI control [6] for accurate tracking of acceleration signals. The low technical requirements suggest that the whole proposed system can be run on board, which starts a new promising line of research for controlling teams of rotorcraft.

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