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Flight Stability in Aerial Redundant Manipulators

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Abstract— **Ongoing efforts toward mobile manipulation from an aerial vehicle are presented. Recent tests and results from a prototype rotorcraft have shown that our hybrid structure increases stability during flight and manipulation. Since UAVs require significant setup time, suitable testing locations, and have tendencies to crash, we developed an aerial manipulation test and evaluation environment that provides controllable and repeatable experiments. By using force feedback techniques, we have designed multiple, dexterous, redundant manipulators that can grasp objects such as tools and small objects. These manipulators are controlled in concert with an emulated aerial platform to provide hovering stability. The manipulator and aircraft flight control are tightly coupled to facilitate grasping without large perturbations in the end-effector.**

I. INTRODUCTION

Unmanned aerial vehicles (UAV) typically try to avoid contact with the ground rather than interact with it. While there have been recent attempts to move past passive surveillance, the field of aerial mobile manipulators is still largely underdeveloped. We seek to go beyond simple claw and hook style grasping and implement truly dexterous aerial manipulation using multiple, redundant manipulators. Compensating reactionary forces becomes critical and mandates a novel control architecture for both flight and arm dynamics. We utilize lessons learned from our prototype vehicle to further advance the state of the art in aerial mobile manipulation.

II. RELATED WORK

Much of the work in aerial manipulation involves quadrotor or co-axial style rotorcraft. Some researchers have performed aerial grasping through the use of 1-DOF (degree of freedom) grippers [1], [2] while others use sling-load implementations to interact with target objects [3]. Although these results are beneficial, they simply implement grasping and not true manipulation. The air vehicle provides the majority of the mobility. Previous work at Drexel University has achieved centimeter position-keeping accuracy on a small helicopter and a hook mechanism to deliver and retrieve cargo [4]. We continue existing efforts in dexterous manipulation that has produced a quadrotor-manipulator prototype vehicle as seen in Fig. 1 along with a MM-UAV (Mobile Manipulating Unmanned Aerial Vehicle) test and evaluation environment [5], [6].

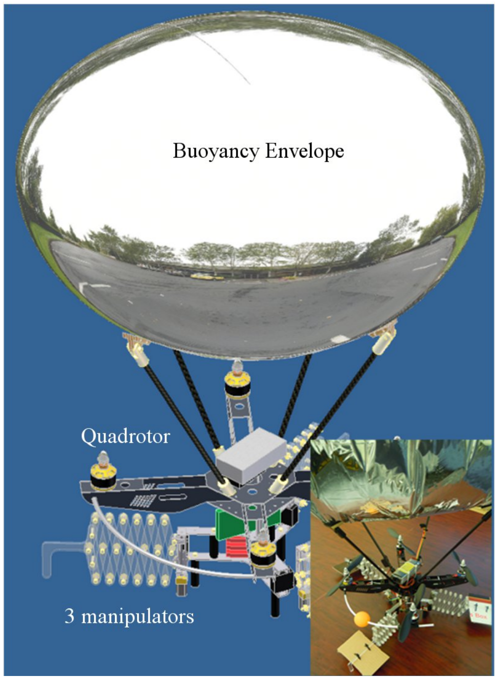

Fig. 1. MM-UAV Prototype

III. MM-UAV HYBRID STRUCTURE

A hybrid rotorcraft structure was designed to compensate for the inherent instability seen in aerial vehicles. To provide restoring forces and dampen rapid tilts, a lighter than air envelop was attached to the quadrotor (Fig. 1). This envelope also increases the moment of inertia of the rotorcraft and slows the pitch and roll changes during flight and manipulation. By analyzing test runs with and without the envelope, we can verify that the hybrid structure does improve flight stability (Fig. 2).

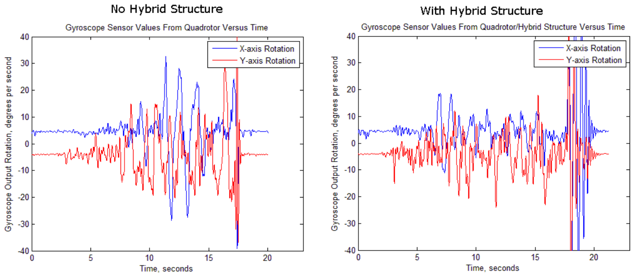

Fig. 2. Gyroscope data showing roll and pitch rotation over time

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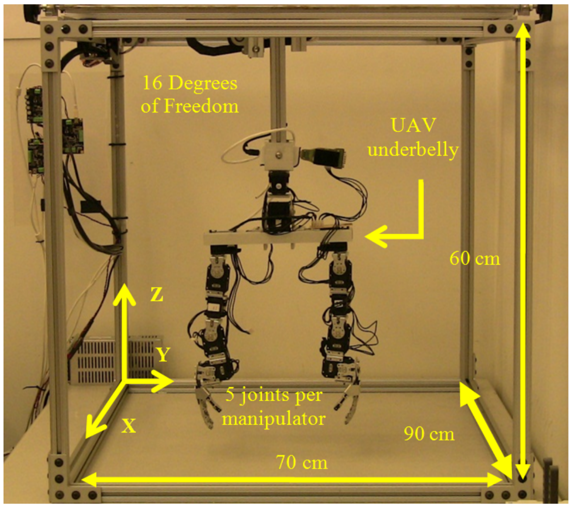

Fig. 3. Mini-SISTR Test Rig

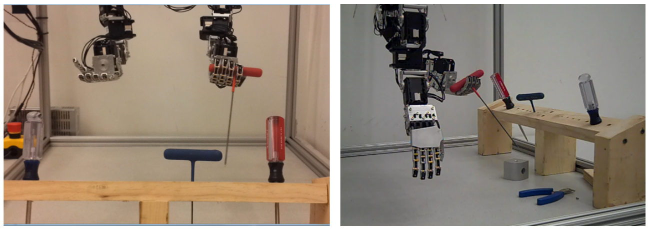

Fig. 4. Tool Manipulation

IV. EMULATING ROTORCRAFT FLIGHT DYNAMICS

In conjunction with building a prototype vehicle, we constructed a miniature gantry test environment based on Drexel's Systems Integrated Sensors Test Rig (SISTR) [7]. The SISTR test environment is well established and we have used the lessons learned from our prototype and applied them to our scaled miniature gantry system. This environment allows for controllable and repeatable experiments (Fig. 3). Using Model Reference Adaptive Control (MRAC), a linearized model of the quadrotor serves as the reference model. The gains are updated according the error between the error of the gantry states and the math model of the rotorcraft. We can measure and control the orientation of the emulated rotorcraft (Euler angles of ϕ, θ, ψ which are roll, pitch, and yaw respectively) along with the x, y, z position. The model incorporates the vehicle dynamics of the quadrotor which uses differential thrust between two counter-rotating motors to provide angle torques and total thrust for position control. To satisfy global asymptotic stability, we chose to implement the following Lyapunov candidate function:

$$V = e^T P e + \Phi^T \Gamma^{-1} \Phi \tag{1}$$

were e is the error between the states of the reference model and the gantry dynamics, P is the positive definite matrix of the Lyapunov equation, Φ is the controller gain vector and Γ is a diagonal matrix whose diagonals are the relative gain update rates. When the error is zero, the gantry movements emulate the rotorcraft motions exactly. Each axis of the mini-gantry is driven by a NEMA 23 bipolar stepper motor and smart servos control the roll, pitch, and yaw angles.

V. FORCE FEEDBACK IN AERIAL MANIPULATION

Even with excellent vehicle position control, relative motions between the UAV and work piece highlight the need for compliant manipulation approaches. Hardware compliance has been employed in [2], but to address the difficulties of using rigid, redundant manipulators, a hybrid force-impedance control strategy was implemented:

$$M_d(\ddot{x} - \ddot{x}_d) + B_d(\dot{x} - \dot{x}_d) + K_d(x - x_d) = -f_e \tag{2}$$

where M_d is the inertia matrix, B_d is the damping matrix, and K_d is the stiffness matrix. The use of hybrid force-impedance control is a well practiced approach for mitigating the impacts of uncertainty on manipulation and provides an interesting additional advantage for aerial manipulation. Measuring interaction forces between the UAV and its environment and can be used to aid overall system stability.

VI. RESULTS AND CONCLUSIONS

We have demonstrated that our hybrid structure improves stability during flight and manipulation and decreases the amount of rotational drift. Nevertheless, the MM-UAV prototype proved to be very difficult to control manually even with the buoyancy envelope. Therefore, we implemented computer-aided control using a motion capture system. Initial results are promising and the prototype vehicle has proven to be an important milestone for current and future work. The mini-gantry test environment allows for rotorcraft emulation and the ability to grasp objects with force feedback (Fig. 4). The tightly coordinated task of flight stability and arm motion prevent large end-effector perturbations during the manipulation task. Refer to the accompanying video presentation for a further illustration of our results.

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