Hexrotor UAV Platform Enabling Dextrous Interaction with Structures-Flight Test

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***Abstract*—In this paper, we present the development of Dexterous Hexrotor, a hexrotor UAV platform with canted thrusters, enabling dexterous interaction with structures. Aerial mobile manipulation is an emerging niche in the field of mobile manipulation. Although there has been a fair amount of study of free-flying satellites with graspers and yielded impressive results, it is hampered a lack of appropriate testbeds for aerial mobile manipulation. Typical helicopters or quadrotors cannot instantaneously resist or apply an arbitrary force in the plane perpendicular to the rotor axis. They lack of force closure (a term from the dexterous manipulation community), which makes them inadequate for complex mobile manipulation tasks. The Collaborative Mechatronics Lab is addressing this instrumentation gap with the development of Dexterous Hexrotor to eventually host a low-cost, lightweight Stewart-Gough platform that can be combined as a macro/micro mobile manipulation system. Based on the concept of force closure, the new type of 6 DoFs hexrotor UAV provides the unique capability of being able to resist any applied wrench, or generalized force-torque. In this paper, we describe how Dexterous Hexrotor provides this important capability. We also describe the flight test which Dexterous Hexrotor is exhibiting holonomic behavior.**

I. Introduction

The field of mobile manipulation [7, 19, 16] combines two broad classes of robots, locomotors and manipulators, yet the potential impact is greater than the sum of the parts. Aerial mobile manipulation is an emerging field within mobile manipulation for which the locomotor is a UAV (unmanned aerial vehicle) [13, 15, 1, 10]. The popular quadrotor has become the main UAV of choice in robotics research, due to its ease of control and low cost. The added mobility and access that quadrotors provide brings a new dimension to the study of mobile manipulation and new challenges, as well.

People have started to apply helicopters and quadrotors to mobile manipulation. Unstable dynamics of the vehicle and coupled object-aircraft motion while grasping objects during flight has been studied[15]. For the manipulation system as UAVs equipped with a gripper, contact forces and external disturbances acting on the gripper and the entire system should be considered[17, 1, 3]. And there have also been works using multiple collaborative UAVs in order to perform transportation tasks[8, 5]. However, when it comes multiple UAVs carrying one payload, there are problems like the interactions between UAVs, physical couplings in the joint transportation of the payload and stabilizing the payload along three-dimensional trajectories. In these studies, single or a team of helicopters or quadrotors with grippers have been used to assist various manipulation tasks and yielded impressive results. But when trying to manipulate an object, these UAVs cannot exert arbitrary forces possibly applied to the object. Because typical helicopters or quadrotors cannot instantaneously resist or apply an arbitrary force in the plane perpendicular to the rotor axis.

Fig. 1. The Hexrotor is performing an inspection task. Note the rotor axes are not parallel

Common UAVs, in general, introduce, and quadrotors in particular,re non-holonomic; in order for them to move forward or sideways, they first have to pitch the entire body of the quadrotor to direct the thrust vector in the desired direction. What this means for aerial mobile manipulation is that the quadrotor cannot resist an arbitrary generalized force/torque. In the parlance of the dexterous manipulation community, it lacks “force closure” [12]. In fact, in one of the first attempts to use a UAV to interact physically with its environment, Albers et al had to add an auxiliary actuator to maintain contact so Newton’ Third Law of equal and opposite reaction would not immediately push the UAV away [2].

Standard helicopters and quadrotors are inherently underactuated for their 6-DoF mobility of position and orientation in space. With only four independently controlled inputs (conventional single-rotor helicopters also have four actuators: main rotor, tail rotor and two actuators on the swash plate), they cannot independently control UAV's position and orientation at the same time. To fix this problem, a quadrotor design with tilting propellers has been presented in [11]. With four additional actuators added for tilting propellers, the 'quad-tilt UAV' now has full control over its 6-DoF mobility. And developed about the same time as our design, a similar non-planar design was introduced by the University of Manchester [4]. Using six variable-pitch/fixed-speed rotors, it is designed to truly achieve full flight envelope, as hover at any orientations and translate in any directions. In these two works, the actuation concept of tilting propellers during flight actually makes it possible to access all 6 degrees of freedom of the robot. But for aerial manipulation tasks, full flight envelop is not important. What is important in resisting any arbitrary wrench is fast response of exerting forces. Tilting propellers during flight using servos may not be fast enough to act on outside wrench.

To solve this specific problem more elegantly, we are developing a hexrotor UAV platform that can instantaneously resist arbitrary forces – in other words, it provides force closure. To perform precise and effective mobile manipulation, this is a property that any locomotor must have, be it ground-based, water-based, or air-based. To achieve this, the thrusters of our hexrotor are canted so that the combined thrust vectors span the space of Cartesian forces and torques. This adds little cost or complexity to a conventional hexrotor. Preliminary work of Dexterous Hexrotor has been published in [18].

It should be noted that we claim Dexterous Hexrotor can "instantaneously resist arbitrary forces". This is not strictly true as Dexterous Hexrotor can only change the torque of its motors instantaneously. The required change in the thrust magnitude is not dependent on torque, for a propeller, but on speed. Therefore, the independent thrust magnitudes and the resulting net force/torque experience a lag due to the inertia of the thrusters. The lag due to the rotor inertia is much smaller than that due to pitching the entire vehicle, as for a conventional quadrotor, and we believe is smaller than the pitching of the variable ϕ concept (which also has to overcome the gyroscopic action of the rotors).

The focus of this paper is on the Dexterous Hexrotor and its suitability as a future carrier of a manipulator for aerial mobile manipulation. Although we do describe the preliminary design of a low-cost, lightweight hex-manipulator (6-DoF Stewart-Gough platform) we have in development, that is not the focus of this paper.

II. Design

To create six independent degrees of freedom in force/torque space, one must have at least six actuators. A conventional hexrotor has six parallel-thrust propellers spaced evenly around the circumference of a circle. Because all thrusters are vertical, no components of the six thrust vectors point along the X or Y axes; they all point out-of-plane, resulting in no in-plane components. So we rotate each thruster a cant angle ϕ around its radius to form a nonparallel design, in-plane components result while still maintaining a symmetric basis of vectors. Variable-speed rotors are used for providing thrust and torque for faster response than a variable-pitch unit.

Fig. 2. Flight-capable prototype of Hexrotor.

A design that uses off the shelf components, preferably those commonly used by modern research quadrotors was chosen to improve cost, compatibility and simplicity.

The motors were mounted on in house designed and fabricated ABS plastic adapters that canted 20° tangentially to the edge on the end of each arm. Position of six motors and their rotation are defined in Fig. 3. By alternating clockwise and counter-clockwise rotations, the torque each motor produced shares same direction with motor force's in-plane components, providing torque around Z axis. X configuration is chosen, so X axis aligns with $Motor_3$ and $Motor_6$.

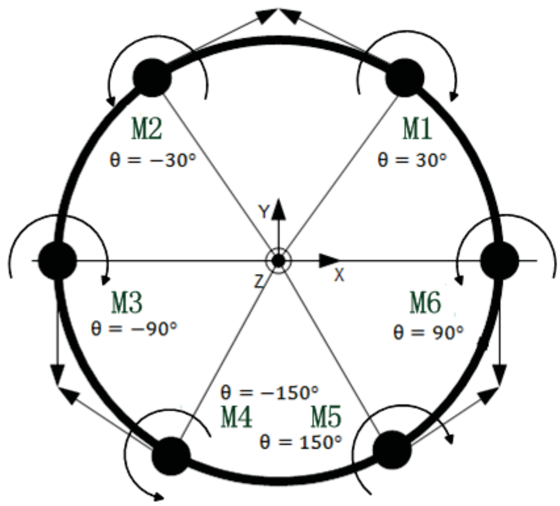

Fig. 3. Motor definitions of the Hexrotor with rotation indicated, where n is the motor number, θ represents angular displacements of the motors.

A. Force Decomposition

The thrust and torque applied on the UAV by each motor can be expressed as

$$\begin{aligned} F_{motor} &= K_1 * PWM_{motor} \\ \tau_{motor} &= K_2 * PWM_{motor} \end{aligned} \quad (1)$$

where K_1 and K_2 are motor-dependent parameters and can be determined experimentally. PWM_{motor} is the command torque sent to the motor via Pulse Width Modulation (PWM).

To compute the net force/torque acting on the UAV from all thrusters, we first decompose each motor's thrust and torque into X, Y, and Z components on the body frame. The components of Cartesian generalized forces from $Motor_1$ can be put into a matrix as in equations (2) and (3).

$$\begin{bmatrix} F_{1fx} \\ F_{1fy} \\ F_{1fz} \\ F_{1\tau x} \\ F_{1\tau y} \\ F_{1\tau z} \end{bmatrix} = \begin{bmatrix} -K_1 * PWM_1 * cos(\theta_1) * sin(\phi) \\ K_1 * PWM_1 * sin(\theta_1) * sin(\phi) \\ K_1 * PWM_1 * cos(\phi) \\ d * K_1 * PWM_1 * cos(\theta_1) * cos(\phi) \\ -d * K_1 * PWM_1 * cos(\theta_1) * cos(\phi) \\ d * K_1 * PWM_1 * sin(\phi) \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} \tau_{1\tau x} \\ \tau_{1\tau y} \\ \tau_{1\tau z} \end{bmatrix} = \begin{bmatrix} -K_2 * PWM_1 * cos(\theta_1) sin(\phi) \\ K_2 * PWM_1 * cos(\theta_1) sin(\phi) \\ K_2 * PWM_1 * cos(\phi) \end{bmatrix} \quad (3)$$

Where $[F_{1fx} F_{1fy} F_{1fz} F_{1\tau x} F_{1\tau y} F_{1\tau z}]^T$ are forces and torques decomposed from the thrust produced by $Motor_1$ and $[\tau_{1\tau x} \tau_{1\tau y} \tau_{1\tau z}]^T$ are Coriolis effects resulting from the torque produced by $Motor_1$. ϕ is the cant angle of each thruster and note that when ϕ is zero, the Coriolis effect only produces a yaw torque as with a normal quadrotor. θ represents the motor's position relative to the body and d is the radius of the UAV.

Then we compute the total force/torque $[F_{1x} F_{1y} F_{1z} \tau_{1x} \tau_{1y} \tau_{1z}]^T$ applied on the UAV by $Motor_1$ as

$$\begin{bmatrix} F_{1x} \\ F_{1y} \\ F_{1z} \\ \tau_{1x} \\ \tau_{1y} \\ \tau_{1z} \end{bmatrix} = \begin{bmatrix} F_{1fx} \\ F_{1fy} \\ F_{1fz} \\ F_{1\tau x} + \tau_{1\tau x} \\ F_{1\tau y} + \tau_{1\tau y} \\ F_{1\tau y} + \tau_{1\tau z} \end{bmatrix} = PWM_1 * \begin{bmatrix} -K_1 C\theta_1 S\phi \\ K_1 S\theta_1 S\phi \\ K_1 C\phi \\ C\theta_1 (dK_1 C\phi - K_2 S\phi) \\ C\theta_1(-dK_1 C\phi + K_2 S\phi) \\ dK_1 S\phi + K_2 C\phi \end{bmatrix} \quad (4)$$

Once one motor is decomposed, we can follow the same pattern and decompose all six motors. Then we can combine these six 6x1 matrices into a 6x6 matrix which is the thrust to force/torque mapping, M_ϕ.

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} = M_\phi \cdot \begin{bmatrix} PWM_1 \\ PWM_2 \\ PWM_3 \\ PWM_4 \\ PWM_5 \\ PWM_6 \end{bmatrix} \quad (5)$$

With K_1 and K_2 determined for our motors, if the cant angle $\phi = 0°$, the thrust mapping is $M_{0°}$

$$M_{0°} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 5.7 & 5.7 & 5.7 & 5.7 & 5.7 & 5.7 \\ 1.33 & 1.33 & 0 & -1.33 & -1.33 & 0 \\ -0.77 & 0.77 & 1.54 & 0.77 & -0.77 & -1.54 \\ 0.13 & -0.13 & 0.13 & -0.13 & 0.13 & -0.13 \end{bmatrix} \quad (6)$$

which would conform to a normal hexrotor design. $M_{0°}$ only has a rank of 4. We have no ability to instantaneously control forces in X and Y through this matrix. But if we cant the thrusters at an angle, for example, at 20°, the thrust mapping becomes $M_{20°}$

$$M_{20°} = \begin{bmatrix} -1.69 & 1.69 & 0 & -1.69 & 1.69 & 0 \\ 0.97 & 0.97 & -1.95 & 0.97 & 0.97 & -1.95 \\ 5.36 & 5.36 & 5.36 & 5.36 & 5.36 & 5.36 \\ 1.21 & 1.21 & 0 & -1.21 & -1.21 & 0 \\ -0.7 & 0.7 & 1.4 & 0.7 & -0.7 & -1.4 \\ 0.65 & -0.65 & 0.65 & -0.65 & 0.65 & -0.65 \end{bmatrix} \quad (7)$$

which would conform to a nonparallel design. This matrix provides a mapping from 6-D actuator space to 6-D force/torque space and has a rank of 6, indicating we have 6 independent controlled degrees of freedom in Cartesian force/torque space.

To control the force/torque applied to the platform, the desired Cartesian force/torque vector is multiplied by the inverted thrust mapping matrix, producing a vector of PWM values (motor command torques) as in equation (8):

$$\begin{bmatrix} PWM_1 \\ PWM_2 \\ PWM_3 \\ PWM_4 \\ PWM_5 \\ PWM_6 \end{bmatrix} = [M_\phi]^{-1} \cdot \begin{bmatrix} F_x \\ F_y \\ F_z \\ \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} \quad (8)$$

B. Control

To help the pilot control Dexterous Hexrotor's orientation and position, a control system based on equation 8 has been developed as shown in Fig. 4. An attitude controller is used to stabilize the Dexterous Hexrotor for hunman controlled flight and control Hexrotor's orientation. A navigation controller is implemented to control Dexterous Hexrotor's position. Dexterous Hexrotor's attitude is measured by a 9 DoF IMU and its position in space is measured by a combination of GPS and barometer.

Unlike common quadrotor, orientation and position control is separate in Dexterous Hexrotor's control system. Dexterous Hexrotor is using a thruster vector (a combination of F_x, F_y, F_z) for position adjustment and this thruster vector is generated without any tilting. When Dexterous Hexrotor's orientation is changed and tilting at an angle, the thruster vector will still point to its target position rather than just point forward. This helps the pilot control Dexterous Hexrotor's

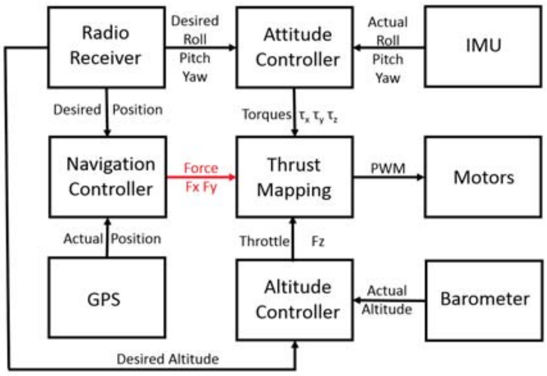

Fig. 4. Block diagram of Hexrotor control system.

orientation and position separately, makes it possible for the Dexterous Hexrotor to move without tilting or tilt without moving.

C. *Aerial Manipulator*

To complete an aerial mobile manipulation system with the aerial mobile base described above, we have begun development of a lightweight, parallel HexManipulator, as shown in Fig. 5. This 6 DoF end effector, which augments the 6 DoFs of the Dexterous Hexrotor, will provide a macro/micro combination for enhanced performance. The HexManipulator will provide the fine adjustments at higher bandwidth that the coarse Dexterous Hexrotor is unable to do. We are developing the software infrastructure on our RecoNode CPU subsystem to control the UAV/manipulator combination in a macro/micro configuration using Khatibs Operational Space formulation [9][6]. This manipulator platform is similar to the configuration of Uchiyama's HEXA parallel robot[14], which provides a large workspace (for a parallel-chain manipulator) based on rotary actuators.

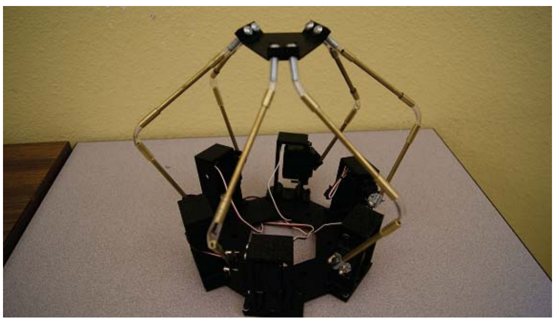

Fig. 5. Prototype of HexManipulator.

There are six links, actuated by a rotary actuator, connecting the base and traveling plate. Each link is a serial combination of a 1 DoF active rotary joint, a 2 DoFs passive universal joint, and a 3 DoFs passive spherical joint. The link is composed of two rods connected by the universal joint and is connected to the base by the rotary joint while it is connected to the traveling plate by the spherical joint on the other end. The 2 DoFs universal joint is implemented with a length of flexible tubing and the 3 DoFs spherical joint is implemented with the same length of tubing plus a passive rotary joint that allows the tubing to twist freely.

Fig. 6. Hexrotor flying with manipulator.

This HexManipulator is installed underneath the Dexterous Hexrotor platform as shown in Fig 6 for tasks as pick, place, insertion, etc. A base connecting the HexManipulator is bolted under the bottom of Dexterous Hexrotor, which makes it easy to install and replace.

III. Experiment

In this section we present three experiments with our prototype to validate our theory and control approach. Two experiments are Dexterous Hexrotor hovering at one spot. One is simply Dexterous Hexrotor keeping its position to show the functionality of position controller. The other one is Dexterous Hexrotor trying to tilt at an angle while keeping its position. Another experiment is Dexterous Hexrotor tracking a trajectory (a straight line) with constant attitude. All experiments are performed in a parking lot with light wind and recorded in the video attached to the paper.

A. *Hovering at one spot*

In the first experiment, the Dexterous Hexrotor is hovering at one spot with 1 meter altitude. With GPS position control, Dexterous Hexrotor will fight the wind with forces in X and Y axes.

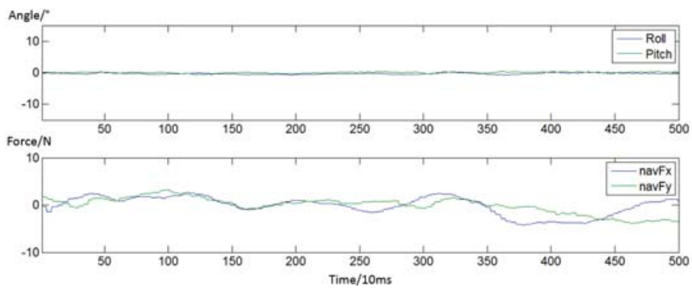

Fig. 7. Measurements of the Hexrotor's attitude and output of navigation controller during first test.

Figure 7 shows Dexterous Hexrotor's attitude and navigation force command output by the position controller during hover.

It shows that Dexterous Hexrotor is keeping level and making adjustment of forces in the plane to keep its position.

B. Hovering with a tilt angle

In this experiment, we demonstrate Dexterous Hexrotor's ability of controlling its orientation while keeping a desired position (hovering with a tilt angle in this case). The Dexterous Hexrotor is trying to roll on one spot. Rolling at an angle would make Dexterous Hexrotor's thrust point to the right, it would generate an acceleration to the right. Since the desired position is not changed, the position controller would adjust the thrust vector and point it back to the target position.

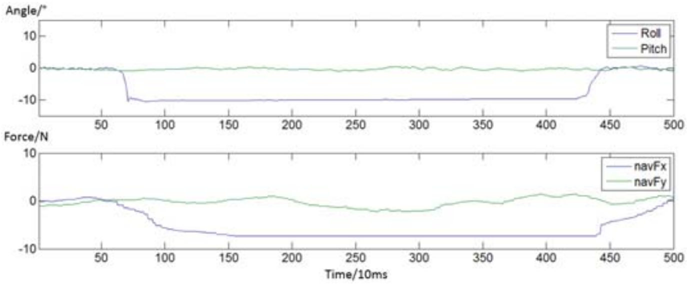

Fig. 8. Measurements of the Hexrotor's attitude and output of navigation controller during second test.

Figure 8 shows the results of the flight. After it rolling at an angle, the Dexterous Hexrotor is producing a negative force in X axis to adjust its thrust vector and let it point to the target position. As explained, this would be unfeasible for a standard quadrotor UAV.

C. Translational flight

In the last experiment, we demonstrate Dexterous Hexrotor's ability of controlling its position while keeping a desired orientation (tracking an arbitrary trajectory with a constant attitude). The Dexterous Hexrotor is commanded to travel along a straight line while keeping level in this test.

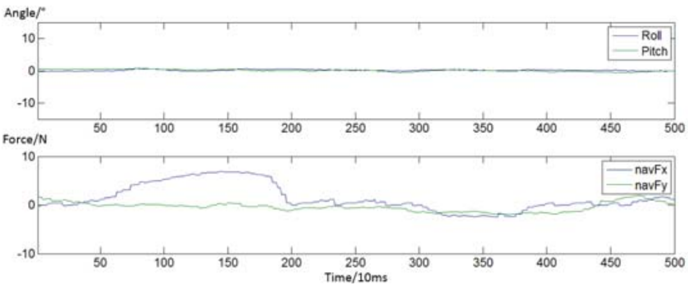

Fig. 9. Measurements of the Hexrotor's attitude and output of navigation controller during third test.

Figure 9 shows the results of the flight. While keeping its attitude at level, the Dexterous Hexrotor is producing a positive pulse of Fx to acquire the acceleration in in X axis and also a small negative pulse later to acquire deacceleration. This proves our Dexterous Hexrotor can perform holonomic behavior.

IV. Conclusion

A truly holonomic aerial rotorcraft that provides force closure has been introduced. The key contribution of this paper is to derive the thrust mapping based on decomposed net force/torque and develop a control system which allows the pilot to control Dexterous Hexrotor's position and orientation separately. A flight-capable prototype has been built and tested.

With the ability of holonomic flight, Dexterous Hexrotor doesn't need a gimbaled mount for the camera while performing an inspection task. Dexterous Hexrotor itself can be used as a pan and tilt camera platform. And when the Hexrotor is flying close to structures or flying in an environment with reduced measurement information, it also has more chance to survive as it can moving around and keep level all the time.

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