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Control of a Fully-actuated Airship for Satellite Emulation

Video Submission

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I. INTRODUCTION

OVER the past four years, researchers at McGill University have developed a novel concept for studying dynamics and control of robotic grasping of objects in space. This problem arises in several applications – those currently under investigation include on-orbit servicing of satellites and removal of space debris. The main difficulty in experimental testing of such tasks is how to emulate the gravity-free environment of space here on the ground. A number of experimental facilities have been developed around the world to emulate the gravity-free conditions for space robotics research. For example, one popular approach involves floating the system under investigation – a robotic arm or a mock-up satellite – on air-bearings on a glass-covered or granite table [1-3]. A few research establishments have invested in neutral buoyancy water tanks for three-dimensional, high-fidelity, albeit very costly, emulation of weightlessness [4]. We have proposed a novel idea which involves using a small helium blimp to emulate a free-floating object. Although not perfect, this concept is simpler, less expensive to implement and is more suitable for 3D emulation of the gravity-free conditions of space.

An experimental facility has been developed in the Aerospace Mechatronics Laboratory to implement this concept in an indoor laboratory setting [5-7]. The main components of our facility are: a six-degree-of-freedom robotic manipulator placed on a 3m linear track, a spherical helium airship 6 ft in diameter, made neutrally buoyant and balanced, a Vicon six-camera system and associated control hardware and software interfaces. This video submission focuses on the control of the airship for satellite emulation.

II. FACILITY DEMONSTRATED IN VIDEO

The airship demonstrated in the video is a custom-design blimp equipped with actuators, sensors, batteries, grapple fixture and electronics to enable it to emulate motion under free-floating conditions. A unique feature of our airship design is a rigidizing frame which circumscribes the bladder bag. The frame is composed of three hoops, each in turn assembled by bolting four quarter arcs. The hoops are made of carbon fibre with honeycomb used for the core material to increase rigidity. All aforementioned equipment for the airship is mounted directly to the rigidizing frame, thus making it easy to accurately define the geometry and mass properties of the system. Another unique and critical feature of the airship is its full actuation – it is driven by six ducted fan propellers, placed on the rigidizing frame in a symmetric arrangement (see Fig. 1) to provide three degrees of freedom in translation and rotation. The motivation for full actuation stems from our objective: to use the airship to emulate a spinning or a tumbling satellite in space.

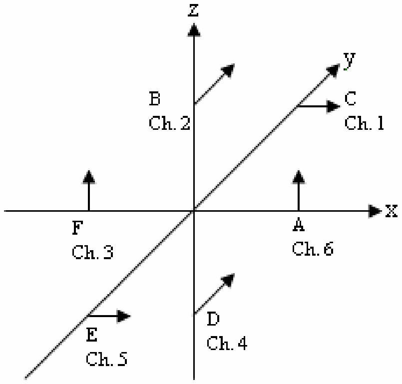

Fig. 1. Propeller orientation

To enable closed-loop control of the airship, a motion capture system from Vicon was procured and installed in the laboratory. The system is comprised of six infra-red cameras equipped with infra-red LEDs. The cameras have been mounted in the laboratory to provide good coverage of the workspace of the airship. The system operates by tracking the motion of retro-reflective markers affixed to the airship and, using Vicon proprietary software, this information is processed to provide three-dimensional position of the markers. In total, 24 retro-reflective markers are mounted on the airship and these have been clustered into six unique rigid bodies with corresponding frames' origins at the center of the airship. The pose information from the visible rigid bodies is streamed at a rate of 120 Hz into Labview – the host environment employed for airship control – where the data is averaged to determine the position and orientation of the airship-fixed frame.

At present, the controller implemented on the airship embodies a full-state feedback control law. In particular, the control inputs are defined by multiplying a matrix of gains

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by the error vector, the latter comprising position, orientation, translational velocity and angular velocity errors expressed in the airship frame, with the quaternion used to parameterize the orientation. Since the Vicon system produces only pose information, the necessary velocity information is currently generated using a finite-difference scheme. Differentiation of position and quaternion is performed on the past 10 samples to minimize noise to latency ratio and the quaternion rate is then transformed to angular velocity. In the future, we will investigate the use of on-board Inertial Measurement Unit and design of non-linear observers to improve state estimation. The gains for the controller have been tuned by trial and error using some general guidelines and numerical tests with the dynamics simulation of the airship. The controller also takes into account the characterized force-voltage relationship for the actuators and the actuator saturation is prevented from destabilizing the system by preserving the direction of the input vector after applying actuator limits.

As alluded earlier, Labview is being used to host the airship controller. A Labview VI has been developed which includes all basic functionalities and user-defined inputs for streaming the Vicon data, control law inputs and settings, input and output data streaming. The VI features thread synchronization to maximize CPU usage and to provide a stable sampling rate.

III. VIDEO CONTENTS

The video submission accompanying this abstract showcases several maneuvers of the airship executed under the closed-loop control described above. In particular, three tasks are demonstrated as described below:

Task 1: Station-keeping. Here we demonstrate the station-keeping capability of the airship, also referred to as hovering. After initial stabilization, the airship is gently pushed by the robotic arm and following this disturbance, it re-establishes its near stationary configuration within 10 sec to an accuracy of 3.5 cm.

Task 2: Rotational motion to emulate tumbling spacecraft. This video segment demonstrates the controller capability to maintain the desired angular velocity vector with components of 0.14 rad/s about X- and 0.2 rad/s about Y- inertial axes.

Task 3: Three-dimensional trajectory tracking. Here, we demonstrate the capability of the airship to track a desired path in three dimensions. The particular trajectory chosen consists of four piecewise linear segments forming a closed loop. No special considerations are made for the transitions between segments other than the airship is allowed to come to a near stop (station-keeping) before continuing on the next segment.

IV. CONCLUSION

This video demonstrates a novel concept for emulating a free-floating object in space for the purposes of studying autonomous robotic grasping of satellites. Already with a very basic controller design, we have been able to demonstrate the capability of the airship to track desired 3D trajectories and to emulate a spinning motion. The use of Vicon multi-camera system provides acceptable accuracy for the present application as our ultimate goal is to develop autonomous controllers capable of intercepting and capturing the target satellite under a variety of conditions and uncertainties. Future work will focus on refining our control strategies for the airship, broadening a repertoire of airship maneuvers, as well as developing path-planning and control strategies for the robot for autonomous and optimal capture of the airship.

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