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Mobile Robotic System for Ground Testing of Multi-Spacecraft Proximity Operations

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Ground testing of multi-spacecraft proximity operations with hardware in-the-loop is currently an expensive and challenging process. We present our approach to this problem, applicable to proximity operations of small spacecraft. We are developing a novel autonomous mobile robotic system to emulate full 6 degree of freedom relative motion at high fidelity. An omni-directional robotic base provides unlimited 3-DOF planar motion with moderate precision, while a micron-class hexapod on top provides high precision, limited 6-DOF motion. This multi-vehicle robotic system is designed to accommodate multiple untethered vehicles simultaneously, allowing for the real-time emulation of relative motion for a large variety of multi-spacecraft proximity operations. Compared with other facilities with similar goals, this approach will allow greater freedom of motion at a target operating cost much lower than existing facilities. We believe these capabilities will be invaluable to the growing number of small and micro satellite programs.

Nomenclature

ASOC = Active Split Offset Castor
DOF = Degree of Freedom
PID = Proportional-Integral-Derivative
RMV = Relative Motion Vehicle

I. Introduction

MULTI-VEHICLE proximity operations of spacecraft, from formation flying to automated rendezvous and docking, represent an extremely active area of current research as industry moves toward smaller, cheaper satellites. Ground based testing of the autonomous control algorithms for multiple vehicles with sensors or docking hardware in-the-loop provides significant risk reduction for such missions. Current facilities for simulation of vehicle motion can be divided into two general categories based upon the level of emulation performed.

One approach is to emulate key aspects of the space environment and use the actual hardware and actuators to achieve the dynamics. While free-fall chambers or parabolic trajectory aircraft can be used to provide a short-term zero-g environment, the method usually used is to simulate contact-free zero-g motion along specific degrees of freedom by reducing friction using air bearings.[1] The Synchronized Position Hold Engage and Reorient Experimental Satellites (SPHERES) project has made use of air bearings in the testing of an actual space-based micro satellite in a ground-based testbed.[2] Relative motion of 6 degree-of-freedom (DOF) micro satellites has been ground tested in 3-DOF using a laboratory air bearing table and two of the SPHERES micro satellites. For spacecraft reorientation dynamics and control, friction-free rotational motion can be achieved using a spherical air bearing and using reaction wheels or control moment gyroscopes.[3]

Another popular approach is to use robotic positioning hardware to simulate the dynamical motion of some virtual vehicle model. This is a hybrid approach where the dynamics of the subject vehicle is simulated numerically, and this simulated motion is tracked by a hardware platform. Using this approach, hardware items such as sensors or docking mechanisms can be evaluated in realistic relative motion situations. One method of tracking the

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precision motion uses a parallel kinematics device, such as a Stewart platform, to provide high precision motion with good stiffness characteristics. However, these devices typically provide only limited ranges of 6-DOF motion due to the restricted workspace. Other approaches use an array of mobile carriages or gantries to allow for a larger workspace, supplemented with a robotic manipulator assembly that may allow for extra degrees of freedom.

For instance, to test the performance of a sensor, Schaub et al are using a single untethered mobile wheeled robot to emulate the dynamics of a simulated vehicle relative to some target.[4] The Naval Research Laboratory's Proximity Operations Testbed at the Naval Center for Space Technology can simulate the relative motion of two large spacecraft using its dual motion platforms. Each platform uses a large 3-axis gantry crane augmented with a robotic arm to provide 6-DOF positioning of target and pursuer.[5] Similarly, NASA's Flight Robotics Facility at the Marshall Space Flight Center uses a combination of these methods by combining a 6-DOF air bearing robot on a flat floor with a large overhead gantry crane capable of positioning a payload in 6-DOF.[6]

Still another approach involves underwater testing, which allows for practically unlimited 6-DOF motion. However, this imposes significant limitations on the possible testing, and preparation for testing in an underwater environment adds unwanted complexity, especially for simple subsystem tests. Vision based sensors, in particular, can not be easily tested underwater.

In contrast to these facilities, we are developing a relative motion emulator based on multiple mobile platforms, called Relative Motion Vehicles (RMVs), each consisting of an omni-directional robotic base with a hexapod mounted on top. The base provides large motions in 3-DOF, whereas the hexapod provides smaller motion in all 6-DOF to a high degree of precision, so it can be used to "clean-up" the less precise motion of the base. The mobile platform approach provides emulation capabilities similar to NRL's facility, though with a lower payload capacity and several distinct advantages:

1) Allows for un-tethered circumnavigation of two or more vehicles.
2) Mobile nature enables testing or demonstration at any location with a large enough room.
3) Low-cost alternative to larger installations while maintaining high fidelity

This paper presents details on the design of a facility to emulate multi-vehicle on-orbit proximity operation dynamics. The overall concept will be described, followed by detailed information on the hardware, sensor, and software aspects of the robotic vehicles and the facility as a whole. Some example scenarios and applications are examined in detail, and conclusions drawn about the usefulness of the system in the increasing area of small satellite programs.

II. System Architecture

A high-level overview of the system control hierarchy is depicted in Fig. 1. The basic idea is that a base station will run a real-time simulation of the multi-vehicle dynamical system that is to be emulated by the robotics facility. For each RMV, the trajectory is split into a 3-DOF low bandwidth component for the mobile base to track, and a 6-DOF high-bandwidth limited range trajectory tracked by the hexapod. These trajectory trackers will be running onboard the vehicles. Data from the vehicle's sensors and I/O, optionally including any payload I/O, will be relayed back to the base station for use in controlling the motion of the emulated system simulation. An external position

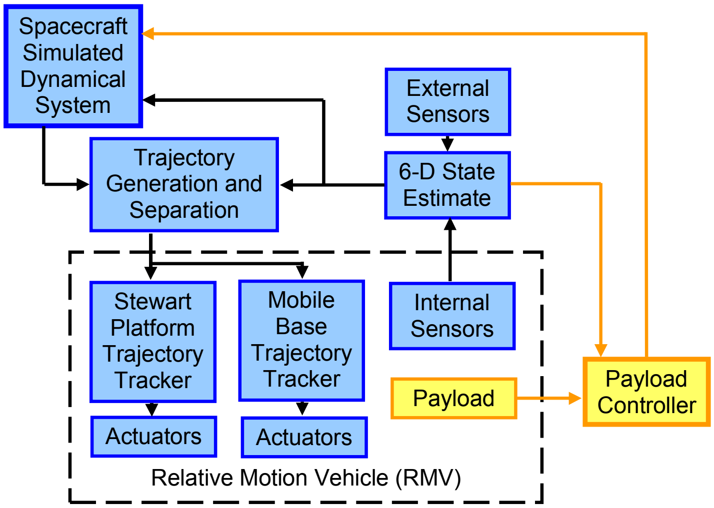

Figure 1: System Architecture depicting onboard vs. external sensing and control

measurement system will be used to supplement the onboard sensors to refine the position and orientation estimates of the payloads on the vehicles.

The dynamics of the desired relative motion system will be simulated in software. The output of this component will consist of the desired payload trajectory which is to be tracked by each RMV. This trajectory is relayed through the trajectory separation component. Trajectory separation algorithms will be used to generate individual trajectories for the base and the hexapod in a way that suits their individual motion abilities. The lower frequency planar motions will be sent to the base while the higher frequency planar motions and the entirety of the non-planar motions will be sent to the hexapod. The base state estimate is also sent to the trajectory separation component so that the hexapod can be commanded to correct for the errors in the commanded base trajectory.

Onboard sensor measurements are sent from the mobile robot to the base station where they are combined with the external inertial position measurements to provide a full 6-DOF state estimate of the payload. This estimate is used by the trajectory separation component as described above. The state estimate is also used by the dynamical system simulation and is sent to any payload controller that may need it.

The payload may consist of a variety of hardware including any combination of docking hardware, proximity sensors, and embedded controllers. There may also be a payload controller module which could be onboard or external to the robotic vehicle.

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III. Relative Motion Vehicles

The robotic hardware consists of two connected motion subsystems, a robotic base and a hexapod. The base is an omni-directional vehicle which provides 3-DOF unlimited range planar motion with moderate precision. The hexapod cleans up the errors in the 3-DOF planar motion while augmenting the motion with an additional 3-DOF to provide full 6-DOF motion capability. Using this combined approach, we can track commanded 6-DOF motions with high precision. The 6-DOF perturbations to the 3-DOF planar motion are limited only by the reach of the hexapod.

A. Omni-directional Robotic Base

The base uses an active split offset castor drive train to achieve fully holonomic omni-directional planar motion with target tracking position errors in the ±1 cm range and heading angle error in the ±0.5º range. Range of motion is 10s of meters (limited by workspace) in translation and unlimited rotation in yaw. Using onboard and external sensors, the position of the base can be resolved in the sub-millimeter range.

The key design consideration of the mobile base is the drive configuration. In order to accurately model the dynamics of a spacecraft docking maneuver, the overall vehicle must be able to accurately follow the desired trajectory. Several different drive mechanisms were considered for the mobile base. One drive method would use individual drive modules, each consisting of a single driven wheel mounted along a motorized vertical axis. The wheel would be steered with the motorized vertical pivot, and then driven using the single motorized wheel. However, delays caused by wheel reorientation could allow the hexapod to saturate and cause errors in the trajectory tracking. To make sure that the mobile base can keep the hexapod within reach of the desired trajectory, the drive configuration must be able to achieve true holonomic omni-directional motion.

Typical holonomic wheels such as the Mecanum wheels have many downsides which make them unacceptable for this application. These wheels are built from many small passive rollers, allowing the wheels to roll across the floor freely in one direction. This system of small rollers can induce vibrations as the weight is transferred between the individual rollers. Additionally, the load is only being carried by several of these small rollers at a time, restricting their load capacity. Open-loop accuracy of the system decreases because the wheels are always slipping, and there is no continuous contact surface between the wheel and the ground.

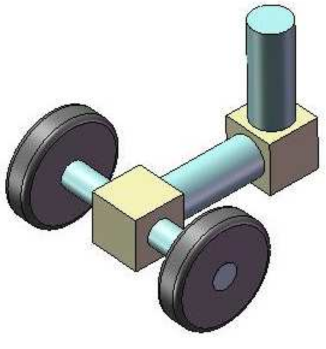
Figure 2. Active Split Offset Castor (ASOC)

Using a standard wheel on an offset castor allows for improved accuracy and load bearing characteristics while maintaining holonomic omni-directional motion as developed by Wada et al.[7] In this configuration, the vertical pivot of the castor is motorized as with the first method described, but since the wheel is offset from the pivot, turning the pivot causes motion orthogonal to the direction the wheel rolls. Advantages of this design are that it uses standard wheels, which have high loading capabilities and low rolling vibrations. The major disadvantage of this drive mechanism is that the scrubbing torque, the friction encountered by rotating the wheel on its edge, leads to large inefficiencies – consider trying to turn the wheels of a car when parked.

An alternate drive method uses drive modules consisting of a configuration known as an Active Split-Offset Castor (ASOC)[8,9]. This design consists of two independently driven motors mounted along a common axis on a castor that is attached to the mobile base by a free vertical pivot. The axis of the wheels is offset in the horizontal plane from the pivot point in the direction perpendicular to the wheel axis. This creates a physical design such that the velocity of the pivot point can be achieved in any planar direction by driving the two independent wheels. The general concept is depicted in Fig. 2. It also can achieve true holonomic motion with no steering dynamics, thus achieving the same advantages as the single offset castor. Though there are six motorized wheels, the total number of motors is the same as the steerable wheels considered previously. Unlike steerable wheels, however, all of the motors are exactly the same, an advantage in terms of motor characterization, maintenance, and replacement parts.

A minimum of three wheel modules is required for stability, and at least two of the castors must be powered to control the three planar degrees of freedom. The third wheel module can be either passive or driven. We selected the option of having all three castor modules being driven and controlled as it allows a more even distribution of motor torques between the motors throughout the envelope of allowable trajectories. Additionally, even "passive" castors have some level of disturbance associated with them, so higher precision control can be achieved by driving all three castors.

As discussed in Section II, the robotic base and the hexapod are controlled independently to track the desired trajectory. To simplify control design, the robotic base was designed to outweigh the hexapod and payload by a factor of 6 so that the motion of the hexapod could be treated merely as a disturbance in the robotic base's control design. Steel was used as the primary material to achieve the desired mass of 220kg, including a removable steel ballast of 75kg. The result is an omni-directional robot with a 1.0m diameter footprint, 0.40m tall with a center of mass only 0.15m off the ground, as shown in Fig. 3. For experiments requiring only 3-DOF motion, the ballast and hexapod can be removed from the robotic base, allowing for payloads up to 100kg.

The robotic base is propelled by 6 Animatics SmartMotors that employ built-in motor controllers. A top level PID controller determines the desired planar body velocity of the vehicle. Though the vertical pivots are free to rotate, their angle is measured by 13-bit absolute rotary encoders. Given the castor angles and the vehicle geometry, there exists a unique set of wheel velocities to achieve the desired body velocity. Those wheel velocities are communicated to the SmartMotors where each motor independently tracks these velocities using an internal PID controller and encoder. Further discussion of control strategies for the RMV can be found in Ref. 10.

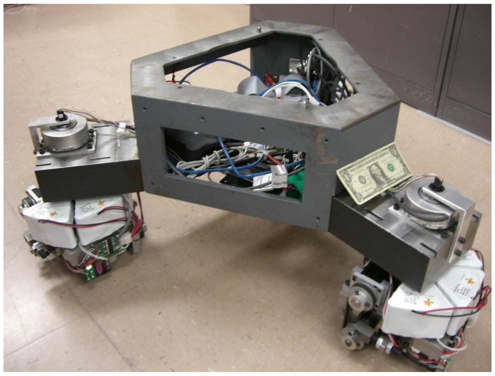
Figure 3. Omni-directional Robotic Base

B. Hexapod

A hexapod, or Stewart platform, is a parallel kinematics device providing 6-DOF positioning. The device is constructed by six variable-length legs mounted on a base plate and supporting an object plate. By varying the lengths of the six legs, 6-DOF motion of the top plate relative to the base plate can be achieved within a workspace defined by the geometry and valid leg lengths of the platform. The parallel nature provides higher stiffness and loading capacities while reducing accumulated errors in comparison with serial kinematics positioning devices.

In our design, a micron-class hexapod manufactured by ALIO Industries[11], as seen in Fig. 4, is mounted on top of the robotic base, which allows for high precision 6-DOF motion relative to the base. In addition to providing the three additional degrees of freedom, the hexapod uses the remaining degrees of freedom to correct for the small tracking errors in the planar trajectory of the mobile base.

The ALIO hexapod is capable of positioning a 10kg payload with micrometer accuracy, and tracks motion profiles with sub-millimeter accuracy. It utilizes a Delta Tau[12] controller running PID controllers on each of the six legs with Renishaw[13] optical linear encoders to provide nanometer level sensing resolution. The hexapod is manufactured primarily from aluminum with a mass of 27kg and can achieve a top speed of 0.2m/s.

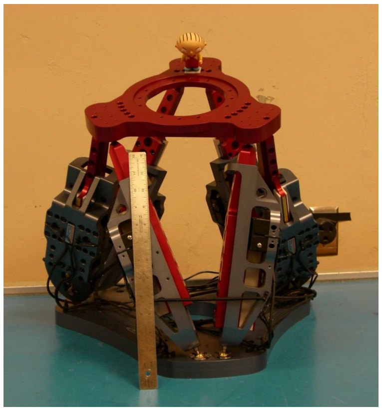

Figure 4. 6-DOF ALIO Hexapod

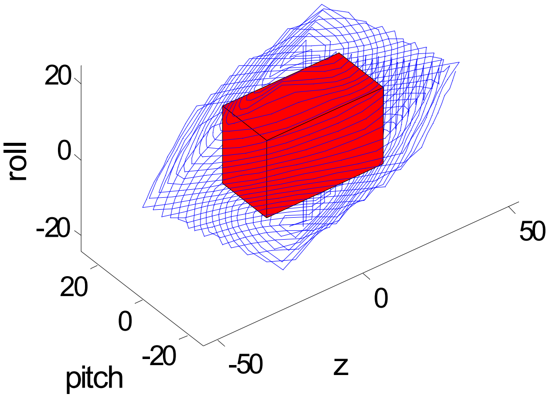

Figure 5. ALIO hexapod workspace when compensating for robotic base errors

The achievable workspace of a hexapod is tightly coupled among all axes, making it difficult to quantify. If none of the other 5 degrees of freedom are displaced from nominal, the ALIO hexapod can move ±5cm in the *x*, *y*, or *z*, and ±20° in pitch, roll, or yaw. However, more representative of the actual workspace would be a box defined in multiple degrees of freedom that is achievable simultaneously. The ALIO hexapod is capable of ±3cm simultaneously in *x*, *y*, and *z*. Still more relevant to our application is the range in pitch, roll, and *z* when the hexapod is displaced to the maximum ±1cm in *x*-*y* and ±0.5° in yaw to compensate for the robotic base errors. The analysis of the highly coupled workspace is shown in Fig. 5, which shows in blue the actual achievable workspace and the red box as a subset of that space. The box shows that even when deflected at the maximum values for robotic base compensation, the hexapod is capable of ±2cm in *z* and ±10° in pitch and roll, simultaneously.

IV. Sensing Systems

To accurately know the position of the payload with high precision, a fusion of several sensor suites is planned. An inertially-fixed sensing system will allow moderately accurate inertial position measurements at moderate intervals, but will need to be augmented by on-board position sensors operating at higher rates and precisions for the payload to track a desired trajectory to sub-millimeter accuracy. Since the hexapod provides micron level accuracy of its 6-DOF position relative to the mobile base, we focus on measuring accurate 6-DOF information about the robotic base and simply add the hexapod displacement to achieve a high accuracy 6-DOF estimate of the payload.

A. Onboard

The most popular means for mobile robot localization is through the integration of the wheel positions, a process known as odometry. In a standard two-wheeled mobile robot, knowing the radius of the wheels and distance between them allows for localization that drifts at a rate of ~1% of distance traveled. Multiple castors provides redundant measurements for odometry, allowing for an order of magnitude reduction in localization errors for a two-castored vehicle.[14]

The mobile robotic base used here features encoders within each motor with an angular resolution at the wheel of 0.03deg. This information is combined with the vertical pivot absolute encoder information, which has a resolution of 0.04deg, to provide an odometry solution. Accuracy is limited by non-ideal conditions such as floor irregularities or wheel slippage, but over short distances odometry is extremely accurate. In this application, the top speed is 0.2m/s, so even with 1% error as a function of distance traveled and traveling at top speed, the robot can move for ½ second before pose error exceeds 1mm. As such the external inertial update does not have to occur at high frequency. Odometry and calibration methods for this three-castored vehicle are described in detail in Refs. 15 and 16.

B. External

Three different inertial measurement systems are currently being evaluated or tested for use in the proximity operations lab facility: Evolution Robotics' NorthStar[17], Vicon's T40 high speed cameras[18], and Metris' iGPS[19]. The NorthStar system consists of multiple IR beacons mounted to the robot and multiple NorthStar Detectors placed around the workspace to provide line-of-sight (LOS) measurements. The Vicon T40 camera utilizes retro-reflective targets placed around the robot and viewed from multiple cameras, again providing LOS measurements. The iGPS system utilizes scanning lasers and active sensors on the robot to provide full 3-DOF position solutions for each sensor.

The nominal use of the NorthStar system is as a planar 3-DOF localization solution where a Detector is mounted on the robot, and two IR spots are projected onto the ceiling. Most of the IR energy output from the projector is lost through this process, and the emulation facility requires a 6-DOF solution. So we designed IR beacons to mount on the robot for the Detector to view directly, thereby increasing signal strength and reducing noise. Each beacon is modulated at a specific frequency to enable the Detector to distinguish between beacons. By having three or more beacons within view of one or multiple detectors, a full 6-DOF solution is possible using only those LOS measurements. Detailed simulation shows that sub-centimeter accuracy is achievable using four detectors placed on tripods around a 300m^2 workspace at a rate of 10Hz, as discussed in Ref. 20. At $1400 for a NorthStar Detector, NorthStar is the low-cost solution to 6-DOF state measurement.

Vicon high-speed cameras have been used in multiple movies and computer games for accurate motion capture of human motion. Strobe LEDs surrounding the camera lens illuminate retroreflective targets on the object to be tracked. The T40 provides 4 megapixel resolution at a rate of 370fps. The camera can output the full image or it can use onboard processing to output only the LOS measurements achieved by centroiding the individual targets, making it easy to use as a measurement system. Over the same workspace as with NorthStar, preliminary simulations suggest that four T40 cameras can provide an order of magnitude improvement in accuracy over NorthStar, though at a cost of tens of thousands of dollars per camera.

The iGPS system from Metris utilizes several rotating IR lasers placed throughout the workspace with sensors that can detect when the laser passes by them. From this information, the position of each sensor can be triangulated to within 0.1mm over a 40m range. Arranging multiple sensors around the robotic base provides extremely accurate 6-DOF localization. Though this is by far the most accurate system, it does require active sensors on the robot, rather than passive beacons or retroreflectors. The cost of an iGPS system is also an order of magnitude higher than the Vicon cameras.

V. System Capabilities

A. Target Performance

In order to meet the desired motion emulation capabilities described in the paper, a set of requirements have been specified regarding the motion performance of the system. These motion and accuracy requirements are based upon a survey of typical proximity operation speeds and proximity sensor accuracies. The overall range and accuracy requirements of the payload motion are summarized in Table 1. The requirements defined are for the combined system of hexapod and base.

Table 1 Motion Requirements

Linear Accuracy (1-σ)	1 mm
Angular Accuracy (1-σ)	0.001 rad
Max Linear Velocity	0.2 m/s
Max Angular Velocity	0.35 rad/s
Max Linear Acceleration	0.05 m/s^2
Max Angular Acceleration	0.17 rad/s^2

B. Scenarios

We anticipate the proposed facility to be invaluable in the emulation and testing of several categories of proximity operations. Note that some experiments may fall into more than one or none of the following categories.

One class of applications is to use the facility to test docking hardware and procedures at a wide range of approach trajectories and speeds. Modeling the contact dynamics of the docking operation can be complex, so using the actual docking hardware can allow greater confidence in the ability of the docking hardware to perform as desired and to evaluate the appropriate response of any kind of supervisory algorithms in relation to different docking scenarios

Another range of applications involves the testing of a wide variety of proximity sensors. By enabling precision relative motion to be specified with sub-millimeter accuracy, the accuracy of relative position sensing systems can be evaluated in a large variety of relative motion situations including combinations of different sensing distances, angles, and velocities. Additionally, different environmental effects such as lighting conditions that may be difficult to model in simulation can be tested in hardware in a dynamic motion situation.

Closed-loop performance of a control algorithm can be tested with some or all of the actual hardware in the loop. With the ability to follow a generated trajectory in real-time with hardware in the loop sensors, processors, and docking hardware, performance of a control algorithm working in conjunction with actual hardware can be evaluated. This control algorithm can be running in software on a PC, or on the actual embedded flight processor in order to accurately take into account the effects of processing and communication latencies involved.

VI. Conclusion

The system presented in this paper will allow for ground-testing of various spacecraft proximity operations, allowing full circumnavigation of multiple vehicles at a fraction of the cost of current two-spacecraft emulators. The design of the robotic base, coupled with the hexapod and augmented with the sensor suite described, allows all of the capabilities of the proposed system. A full simulation modeling all vehicle dynamics, sensor uncertainties, control algorithms, communication latencies, and processing delays is being developed alongside development of the hardware subsystems.

Acknowledgments

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