EXPERIMENTAL VALIDATION OF DOCKING AND CAPTURE USING SPACE ROBOTICS TESTBEDS

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EXTENDED ABSTRACT

INTRODUCTION

This presentation describes the application of robotic and computer vision systems to validate docking and capture operations for space cargo transfer vehicles. Three applications are discussed: 1) Air bearing systems in two dimensions that yield high quality free-flying, flexible, and contact dynamics; 2) Validation of docking mechanisms with misalignment and target dynamics; and 3) Computer vision technology for target location and real-time tracking.

All the testbeds are supported by a network of engineering workstations for dynamic and controls analyses. Dynamic simulation of multibody rigid and elastic systems are performed with the TREETOPS code. MATRIXx/System-Build and PRO-MATLAB/Simulab are the tools for control design and analysis using classical and modern techniques such as H-infinity and LQG/LTR. SANDY is a general design tool to optimize numerically a multivariable robust compensator with a user-defined structure. Mathematica and Macsyma are used to derive symbolically dynamic and kinematic equations.

AIR BEARING TESTBEDS

These testbeds provide unconstrained motion in a three degree-of-freedom (DOF) environment with dynamics that closely approximate zero gravity. This allows hardware simulations of contact dynamics with realistic mechanisms, materials, and inertial properties. Large manipulator with link flexibility. The primary flat floor air bearing surface is approximately 20x30 feet and is maintained within a class 10,000 clean area. The surface is made of a two-part epoxy specially formulated for self-leveling properties. A non-contact optical position sensor system is used for performance measurement of all systems operating on the flat floor. An adjacent air bearing surface is located in a thermal chamber for testing hot and cold mechanisms. Smaller air bearing testbeds are located on an optical table with a glass top.

Free-Flying Servicer Vehicle

This testbed is a planar system consisting of a vehicle and two manipulators. The kinetic properties of the servicer testbed are scaled to approximately match those of the Flight Telerobotic Servicer (FTS) mounted on a low-mass vehicle such as the Manned Maneuvering Unit. A high-mass and inertia vehicle is simulated by adding mass to the vehicle frame. The testbed vehicle has three maneuvering DOF: two translational and one rotational. The primary manipulator has four DOF with modular and interchangeable joints and links; link lengths and mass properties can be adjusted to simulate desired manipulator characteristics. The three DOF secondary manipulator has similar capabilities, implemented with flight prototype components. The vehicle has mounting points

for additional test mechanisms and interfaces. These include a docking grapple compatible with the large space manipulator gripper; flexible solar panel appendages; and a generic docking mechanism adapter.

The vehicle has been designed for self contained operation, requiring no external support except for telemetry. Eight cold gas thrusters provide translational and rotational thrust from the onboard nitrogen supply. The thrust level of the thrusters is adjustable. The vehicle also carries a reaction wheel torquer, which consists of a large DC motor coupled to an inertial load. Electrical power is provided by rechargeable batteries to operate the actuators and the processing and control electronics. Air from onboard tanks is used for flotation of the bearings and for the thrusters. The control system is distributed, with the servo-level processing onboard and a wireless communication link for teleoperated and autonomous operation. Accelerometers and a rate gyro measure vehicle motion for closed-loop control. A stereo video camera pair is mounted on a three DOF platform for autonomous vision sensing. The control system is structured hierarchically and incorporates both autonomous vision-based guidance and delayed remote manual control.

Experimental studies have been conducted with the manipulators to examine: 1) inertia matrix decoupling schemes, 2) contact stabilizing controllers, 3) position- and torque-based impedance controllers, 4) the effects of teleoperation force reflection time delays, 5) system identification of large payload mass properties and nonlinear arm dynamics, and 6) control of flexible payloads. The vehicle has been tested on the air bearing floor and is presently receiving upgraded control system electronics.

This testbed provides an integrated validation of vehicle control algorithms, docking sensors, and capture mechanisms. The manipulator may be used as a capture device to avoid an impact type docking procedure. Proximity operations including fly-around can be performed with either a fixed or free-flying target vehicle.

Large Space Manipulator

The LSM testbed is a planar 15 foot long arm with three DOF built to emulate the dynamics of long, crane-like space manipulators such as the Space Shuttle RMS, the Space Station RMS and the (future) Space Crane. In its current configuration with thin flexible links, the fundamental vibration frequency for the arm extended is 0.2 Hz with joints locked. This manipulator also has modular and interchangeable joints and links which can be varied to simulate desired manipulator characteristics. The actuators and link interfaces are identical to the smaller manipulator on the servicer vehicle, allowing a large crane-like arm on the free-flyer.

As a baseline for closed-loop performance, two initial classical control designs have been implemented digitally with a 200 Hz sampling rate. The first controller is a low bandwidth, proportional plus derivative (PD) design using joint position and velocity feedback. Higher closed-loop bandwidth with active control of the arm dominant elastic modes is achieved using an x-y tip position sensor compensation (second-order lead) closed around co-located joint rate feedback loops. Shaping filters are used to gain stabilized the arm higher frequency vibration modes. Future work will demonstrate autonomous capture of a free-flying payload using a vision-based proximity sensor to track the relative position of the end-effector.

With rigid links, this manipulator can simulate relative orbital motion of target vehicle in the orbital plane. In this scenario, the target vehicle is attached to the LSM and the force/position control loop simulates target structural dynamics during docking. This approach integrates the sensing and control aspects of the free-flying vehicle system with realistic relative motion and dynamics of the target.

INTEGRATED TELEAUTONOMY TESTBED

This laboratory contains three commercial 6 DOF electric manipulators whose control systems have been replaced with custom controllers. The largest of these has a reach of several feet with a capacity above 100 lb. Six-axis force/torque sensors are mounted between each manipulator's wrist and end effector. Video cameras are also mounted to the wrist of each manipulator. The control system architecture of this testbed is hierarchical and incorporates servocontrol, trajectory control, path

planning, and task planning layers. Computer vision has been incorporated into the control system for real-time vision-guided manipulation. A multi-level operator interface provides supervisory control of the system at all levels in the controller hierarchy. The servo controllers for the manipulators accept Cartesian position commands from either hand controllers or from a higher-level trajectory generator. The commanded position is modified by an impedance control loop, also known as active compliance, based on the sensed forces and torques.

We have analyzed and simulated the constrained contact dynamics between mechanical components manipulated by robots. These simulation models have been validated using robotic testbeds operating in one, two, and three dimensions. This same capability provides an analytical basis for predicting the operating characteristics of a spacecraft docking system.

This testbed provides the capability to validate the operating regime and performance of docking mechanisms in three dimensions. The mechanisms will be mating at varying velocities with carefully controlled misalignments in position and orientation. The manipulator is controlled with force feedback from the force/torque sensor mounted between the toolplate and the docking mechanism. The force/position control loop can simulate a model of the supporting structure's dynamics. The combined workspace of two manipulators is several feet, allowing moderate free-body reactions to be simulated.

COMPUTER VISION

Accurate estimation of target vehicle position and attitude (*i.e.*, pose) is critical to successful autonomous rendezvous and capture. Computer vision is a sensing technique that can provide accurate pose information at relatively close ranges.

We have developed a variety of experimental and analytic tools to evaluate the accuracy, robustness, and speed of computer vision algorithms running on different processing architectures. We have developed software simulations as well as actual hardware measurement techniques (using laser interferometers and theodolites) to measure the accuracy of camera calibration and pose estimation algorithms. We have integrated a vision system into the NASREM-based Teleautonomy testbed described above, to demonstrate the robustness of vision-guided manipulation tasks. Finally, we have three different image processing systems available to support evaluation of real-time performance: a multiple Digital Signal Processor (DSP)-based system (Androx), a video-rate pipelined system (Datacube), and a massively parallel system with over 12,000 bit serial processors (Martin Marietta's GAPP).

An representative example of our experience in this area was a recent experiment to determine the accuracy of pose estimation from single cameras. We compared five different pose estimation algorithms using real images with very accurate ground truth data. A planar target containing circular markings was moved through a series of positions and measured very accurately (to 0.002" and 0.004°). These images and ground truth data were originally created for the FTS program as part of an effort to develop a visual positioning sensor that would be used to verify the positional accuracy of the robot arm on orbit during Demonstration Test Flight 1. We found that vision is very accurate (better than 0.05" and 0.5°) at very close ranges (2' or less); the translational accuracy scales linearly with range.

By designing appropriate targets (*e.g.*, with high contrast markings), the computational power needed to extract the target features is minimized. In our robotics work, we can estimate target pose at a rate of 10 Hz using a DSP board hosted on a Sun compatible workstation. Faster DSP's, which are available and space qualified, could boost this rate to 30 Hz. This real-time pose estimation capability can be used in either the 2D or 3D testbeds for simulating rendezvous and capture operations.

These capabilities have been developed in the Intelligent Systems and Controls group of our Research and Technology department. Development of the flat floor and air bearing testbeds was done entirely under Martin Marietta internal funding.