Robot Navigation for Space Station Environments

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ABSTRACT

Future space exploration missions will increasingly depend on the seamless integration of human-robot systems to accomplish critical mission goals. An emerging class of free-flying robots, such as the Astrobee platform (currently under development as part of the *Human Exploration Telerobotics 2* project) appears to hold great promise in complementing human activities. For example, such free-flying robots may work with crew on board the International Space Station (ISS) or the planned Lunar Orbital Platform-Gateway (LOP-G) to help automate environmental data collection or serve as a maneuverable remote monitoring platform for ground control. To achieve these goals, free-flyers will need to safely and effectively navigate confined space station environments in a human-aware manner. This work explores the design of new trajectory planning algorithms that will enable free-flying robots to operate in confined space station environments in close proximity to crew.

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1 INTRODUCTION

In order for robots to effectively work and collaborate with crew, they must be able to safely navigate confined space station environments. At the same time, it will also be critical that robots convey their intentions to crew, such as indicating an intended direction when navigating across station modules. Our work explores this context in the pursuit of developing a motion planner for free-flying robots operating in confined environments that considers human comfort and safety while also enabling the robot to achieve task outcomes.

In particular, we consider a scenario in which a human crew member and a free-flying robot both approach a node linking station modules from opposite directions. This scenario is analogous to terrestrial scenarios in which a human and a robot (or two humans) may approach one-another in a narrow hallway or doorway. We focus on developing a motion planner that allows the motion of the robot to communicate its intent to proceed first or yield. Below, we briefly describe related work on communicating robot intent and then describe our optimization approach.

2 RELATED WORK

Successful collaboration and teamwork depends on having team members communicating their intent through various signals. For example, human teams may coordinate their activities with a variety of nonverbal behaviors that augment speech, such as gestures and gaze cues. The field of Human-Robot Interaction (HRI) has explored a variety of ways in which robots might also communicate intent to human teammates [4], including:

- **Gaze:** Prior work has shown that gaze can also be a powerful cue for robots and virtual agents [1, 7, 13, 17]. However, non-humanoid or appearance-constrained robots (e.g., free-flyers, lunar rovers, etc.) may not be able to demonstrate gaze behaviors.

- **Gesture:** Similarly, past researcher has investigated how robots might use human-like gestures to convey information to users, but again such cues may be infeasible for robots lacking a humanoid morphology [9, 15].

- **Sound:** Another solution for conveying information is by using explicit auditory cues, ranging from simplistic non-linguistic utterances (e.g., beep or chirp) to speech [4, 12, 14]. However, auditory cues may not be feasible for free-flying robots as such cues may be washed out by operational (rotor, motor, etc.) noise. Moreover, space station environments typically enforce strict limitations on sound.

- **Visual Displays:** Using images, color, shape, and other characteristics represents a promising medium to convey a wide range of information including operational plans, physical activities, and proximity [6, 8, 10, 18]. Lights are a subset of visual displays, in which a single LED or LED strip is used. Using lights to convey direction has been explored by [2, 17].

- **Implicit Motion:** A great deal of research has explored algorithms for generating implicit motion cues for robot [3, 5, 11],

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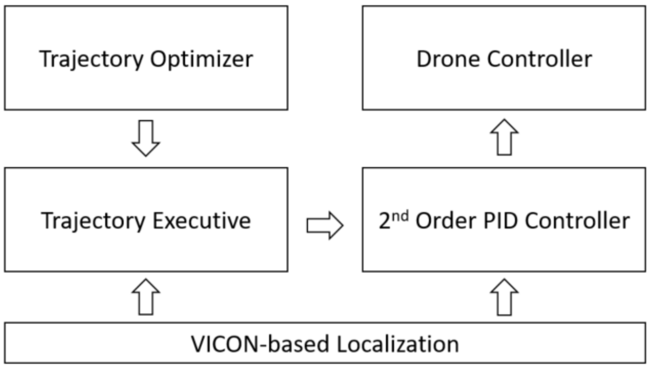

Figure 1: System Architecture

for instance generating legible motions for robotic manipulators or socially appropriate navigation for ground-mobile platforms. Other research has investigated how free-flyer motion can be altered to increase predictability and legibility [16], although such work has yet to produce motion planning algorithms capable of generic use in space station environments.

In this work, we look at nonverbal communication in closed shared spaces, building on past work investigating how robot motion can represent an implicit communicative cue. Robot motion can be robust to various changes in environment (e.g., noise and lighting) and may be highly intuitive for users. Although, Dragan et al. [5] explored the development of a planner for implicit motion for a robotic manipulator, to our knowledge there has been no work done that explores implicit motion in closed shared spaces, such as those in space station environments, for free-flying robots. Space station environments incur unique operational requirements, including constratins on velocity and acceleration due to safety concerns, a consideration of navigation in very confined spaces, and an understanding of how to operate in an environment that doubles as a human living and work space in a socially appropriate manner. In this work, we examine each of these aspects in the development of safe and communicative navigation algorithms for arbitrating human-robot passing in confined spaces.

3 SYSTEM DESIGN & IMPLEMENTATION

The goal of our approach is to produce a trajectory ξ^* that minimizes a cost function that incorporates features important for predictability and legible turn-taking with humans. In other words, this cost function should bias the trajectory's intermediate points to produce motion that is not only perceived as safe by the human, but also usable to negotiate demanding spatial utilization constraints. To accomplish this, we propose a system consisting of the following components:

- **Trajectory Optimizer:** Given a start and goal pose for the drone, produce a trajectory consisting of intermediate points that minimizes a specially designed cost function.
- **Trajectory Executive:** Given a trajectory, the executive monitors waypoint occupancy and governs progress, updating the target position for the PID controller to generate smooth trajectory-following behavior.
- **PID controller:** Given a pose and velocity goal, this controller commands the drone to achieve the desired position, orientation, and velocity.

Our reference implementation utilizes ROS (Robot Operating System) and will be made available as a ROS package containing nodes for each of the specified components. Our work also relied on two readily available ROS packages, "Vicon Bridge" (for communicating with our motion capture system) and "Bebop_Autonomy" (for drone control).

3.1 Trajectory Optimizer

The trajectory optimization is implemented as a graph search problem, incorporating 1st and 2nd-order pose information into each vertex (state) and using a simple dynamics model to inform transitions (edges). Our approach probabilistically expands the considered state graph by sampling potential expansions from current-best vertices, subject to allowable transitions given the drone dynamics model. In practice, this amounts to performing rejection sampling over a hypersphere surrounding the current vertex, only accepting those points that represent viable next-states. In our implementation, we utilized a radius of 0.05 for each feature, sampling 100 points per expansion. As the radius and sample density increase, the quality of solution can be increased.

The search uses the L^2-norm between the goal state and the state being accessed as a heuristic cost-to-go, as it is an admissible relaxation of the true cost function which minimizes distance traveled in addition to human-relevant costs.

Each state cost f is expressed as,

$$f(x) = g(x) + h(x) \tag{1}$$

$$h(x) = \sqrt{\sum_k (x_k - g_k)^2} \tag{2}$$

$$g(x) = \begin{cases} \infty, & \text{if } |x - prev(x)|_2 \geq \epsilon \\ c(x) + g(prev(x)), & \text{otherwise} \end{cases} \tag{3}$$

$$c(x) = w_0 * |x - prev(x)|_2 + \sum_n (w_n * F_{R_n}) + \sum_m (w_m * F_{H_m}) \tag{4}$$

Which x is state of the aerial robot and descried by a 12×1 vector contains robot's position, orientation, and associated velocities. F_R present a group of processed features which are related to the physics and dynamics of the aerial robot. The list of F_R features are:

- Altitude of the robot
- Velocity of the robot
- Distance from the center of hallway
- Rotation (CC or CCW)
- Bounce (variance of the Z positions)

F_H present the features which relate to the user interacting with the aerial robot, which are as below:

- Position and orientation of the human

- Velocity of the human
- The height of the human

where, h is an admissible heuristic cost-to-go, g represents the shortest-path-cost incurred, and $prev(x)$ is a function returning the preceding vertex in the shortest path to x. *epsilon* represents the spherical distance imposed by the sampling radius defined above.

3.2 Trajectory Executive

The trajectory executive gets an ordered list of target poses from the trajectory optimizer, and proceeds to send these points to the PID controller to progress the drone through the desired path.

The trajectory executive has two primary tasks, monitoring waypoint attainment and monitoring for human occupancy. The executive also has control over a form of implicit trajectory smoothing, by increasing the tolerance for detecting whether a pose has been achieved (and thus sending the next pose to the PID controller). The executive is also responsible for maintaining safety in the presence of objects unaccounted for by the trajectory optimizer, as trajectory generation is not presently being performed online during trajectory execution.

3.3 PID controller

We implemented a second order PID controller to reach waypoints specified by the trajectory optimizer. Our PID controller runs at 20Hz and precisely controls the velocity, position, and orientation of the free-flying robot.

To simulate this operation in terrestrial settings, we are currently using a Parrot Bebop as an analog robotic platform. This robot lacks onboard sensing capabilities sufficient for accurate localization, thus the PID controller currently uses motion tracking cameras embedded in the environment (Vicon Motion Capture) to track the robot. The PID controller gets two inputs: current state of the aerial robot from the Vicon system and the goal position from the Trajectory Executive. We used the Ziegler-Nichols method to tune our KP, KI and KD.

4 ONGOING AND FUTURE WORK: EXPERIMENTAL EVALUATION

We are currently conducting an experiment to evaluate our motion planner within the context of close proximity navigation. Our experiment tasks human subjects with navigating through a doorway while a free-flying robot attempts to also travel through the doorway, but in the opposite direction. Each participant is given a cue card that states whether they should go through the doorway immediately or yield the right-of-way to the robot. At the same time, we manipulate our trajectory executive and cost function as an analog to the importance of the robot's simulated task, which can either incur a high penalty for waiting (i.e., the robot prefers to cross first) or does not impose a penalty (i.e., the robot has no preference). Thus, our experiment takes the form of a 2 (human preference) $\times$ 2 (robot preference) full factorial design with the following conditions:

- Both the human and robot intend to cross first
- The human intends to cross first while the robot has no preference, so can go second
- The human has no preference and the robot intends to cross first
- Both human and robot have no preference.

The condition in which neither the robot nor the human has any preference or priority can potentially lead to deadlock, where each waits for the other to go first. In this case, after a certain amount of time, the robot moves slowly toward its intended goal while observing any corresponding human movement. If the human appears to still be waiting for the robot to pass, the robot continues and the situation devolves to that when the robot has priority, otherwise the robot hovers until the human passes through. In this study, our dependent variables include measures of perceived user safety, comfort, and trust along with objective measures such as human and robot wait time and path taken.

5 CONCLUSIONS

In this work, We have proposed a planner that may generate human-interpretable motions in closed shared spaces, such as those found within the ISS or future LOP-G. To our knowledge, no prior work has been done in this domain, yet it is critical for achieving successful human-robot collaboration and coordination in future space missions. We have yet to complete an evaluation of our model but we believe that our work may help increase the usability of free-flying robots in space exploration missions.

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