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Motion planning and control of robotic manipulators on seaborne platforms

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ABSTRACT

Robots on ships have to endure large inertial forces due to the non-inertial motion of the ship. The ship motion affects both the motion planning and control of the manipulator, and accurate predictions can improve performance substantially. It is thus important to investigate to what extent it is possible to predict the future motion of a ship. Based on these predictions, this paper presents a new approach to motion planning and control of such manipulators. It is shown that the effects of the non-inertial forces can be eliminated—in fact, the robot can even leverage the inertial forces to improve performance compared to robots on a fixed base. In particular it is shown that by including the inertial forces in the motion planning the wear and tear on the robot due to these forces can be reduced substantially. To perform realistic experiments a 9-DoF robot is used. The first five joints are used to generate the real ship motion, and the last four joints are used for motion planning. The dynamic coupling between the first five and the last four joints is thus exactly the same as the dynamic coupling between a ship and a manipulator, which allows for very realistic experiments.

1. Introduction

Robotic manipulators on non-inertial platforms such as ships have to endure large inertial forces due to the non-inertial motion of the platform. When the non-inertial platform's motion is known, motion planning and control algorithms can try to eliminate these perturbations. In some situations the motion planning algorithms can even leverage the inertial forces to more economically move to a target point. However, for many non-inertial platforms, the motion is unknown.

This paper first investigates to what extent it is possible to predict the future motion of a ship. Using real ship motion measurements one can study how the uncertainty of the prediction algorithms changes with the prediction horizon. Then a new motion planning approach that finds the optimal trajectory from an initial to a target configuration based on the predicted future motion of the ship is presented. It is also shown that by including the uncertainty in the cost function the maximum torques needed to reach the target configuration can be reduced.

Due to the stochastic nature of the ship motion and the dynamic coupling between the ship and the manipulator, empirical studies are extremely important to validate both the ship motion predictions and the motion planning algorithms. To perform realistic experiments a 9-DoF robot is used. The first five joints are used to generate the real ship motion, and the last four joints are used for motion planning. The dynamic coupling between the first five and the last four joints is thus exactly the same as the dynamic coupling between a ship and a manipulator. It is thus possible to perform very realistic experiments as ship motions measured from a real ship are used to generate the actual motion and at the same time realistic ship motion predictions are used as inputs to the motion planner. To get statistically meaningful results several simulations are performed to confirm the experimental results.

Ships and other seaborne platforms are expected to become increasingly unmanned in the future and the need for autonomously operating robots for surveillance, maintenance, and operation will continue to increase over time (Kitarovic, Tomas, & Cisic, 2005; Love, Jansen, & Pin, 2004). The demand for unmanned operation becomes even higher in harsh environments such as high sea state (Fig. 1), when it can be dangerous for human operators to be exposed. High sea environments are not only dangerous to human operators, they also pose significant challenges for robotic control. Large inertial forces will influence the manipulator and, when not anticipated and accounted for, can make the operation inaccurate, extremely energy demanding, and sometimes even impossible due to torque limits. The inertial forces thus need to be taken into account in the motion planning of the robot.

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Fig. 1. A ship in high sea. The wave forces can result in very high accelerations in the ship motion. (©2010 IEEE)

In From, Duindam, Gravdahl, and Sastry (2009) the authors solve the problem of optimal motion planning for a robot mounted on a ship *under the assumption the base motion is known for all times.* The approach includes the ship motion in the trajectory planning problem and an optimal trajectory in terms of actuator torques is found. However, in most practical situations the forces acting on the ship due to the interaction with waves and wind are very irregular and one cannot expect to know the base motion for all times (From, Gravdahl, & Abbeel, 2010).

In this paper a model predictive control scheme is adopted in the sense that a ship model is used to predict the future motion of the ship, and that these predictions are updated at every time step using feed-back from the ship measurements. The extent to which it is possible to obtain accurate ship motion predictions can thus directly affect how well the inertial forces can be compensated for or even taken advantage of. However, the accuracy of the ship motion prediction not only directly determines how optimal a solution one can achieve, it also affects the computational requirements. In a receding horizon setting, where the optimal control input sequence is re-computed at regular intervals, the computational burden will increase for an inaccurate model: for an inaccurate model the initialization point taken from the previous solution is further away from the optimal solution. In addition to affecting the choice of horizon the modeling error thus directly determines the frequency for which the optimal control or optimal trajectory can be recalculated.

An important contribution in this paper is the use of real empirical data for both the experiments and the simulations. Much of the literature on ship motion prediction uses computer generated data to verify the accuracy of the prediction algorithms, which leads to unrealistically small errors in the predictions. An important difference between the work presented here and previous work is thus the use of real full-scale ship motion data to test the performance of the ship motion prediction algorithms.

Another important contribution is the realistic experiments. For the experiments a 9-DoF robot was used. The real ship motion was fed into the first five joints, generating a very realistic ship motion, and the last four joints are then used for optimal motion planning for a 4-DoF robot on a moving base. Because the yaw motion is practically zero, the five degrees of freedom representing the ship motion and the four degrees of freedom representing the manipulator allows for experiments performed on a 4-DoF robot mounted on a base with exactly the same motion as if the robot had been mounted on a ship. The predictions used are based on the real ship motion and the experiments thus give important information on to what extent it is possible to compensate for the inertial forces.

Experiments are important to study how the motion of the base affects the manipulator dynamics. The experiments also allow for direct measurements of the torques that act on the manipulator due to the inertial forces. This paper thus presents, for the first time, a detailed study of how the inertial motion of the ship maps to the joint torques. This is used to show that the forces that act on the manipulator due to the waves are significant and cannot be ignored in the motion planning and control of the manipulator.

Stochastic uncertainty is present in a wide variety of systems, ranging from mechanical systems and process control to finance. In general, receding horizon control is a well-suited control scheme to deal with uncertainties, but most approaches do not use information about the probability distribution governing the uncertainty and they only assume that the uncertainty is bounded. Thus, the information about the probabilistic distribution is ignored and the worst-case representation of the disturbances or constraints often leads to a conservative solution.

In this paper a new motion planning algorithm that also minimizes the variance of the controlled state is presented. First, real ship motion measurements are used to calculate the variance of the predictions of the forced state. It is found that the variance is different for roll, pitch and yaw. Second, it is shown how to use the Extended Kalman filter to find how the variance in the forced state maps to the variance of the controlled state, i.e., how the uncertainties in the ship motion predictions map to uncertainties in the robot state. The general idea of this approach is to exploit the fact that there are some components of the ship motion that are more difficult to predict than others. Also, for different configurations of the robot, the inertial forces will affect the robot differently. Thus, by including the variance in the cost function one can force the motion planner to choose a trajectory that is less affected by the largest and most uncertain components of the base motion. When a receding horizon approach is applied, it is found that by augmenting the cost function to also include the variance it is possible to choose a longer horizon than when the variance is not included.

The paper is organized as follows: Section 2 gives a short introduction to ship-manipulator modeling, presented in more detail in From et al. (2009). The ship motion prediction algorithms used are presented in Section 3, and in Section 4 it is shown how to use these predictions to improve the motion planning and control of a robotic manipulator on a moving base. The simulations and empirical studies are presented in Section 5. Related research and references are discussed in Section 6. A preliminary version of the work presented here appeared in From et al. (2010).

2. Ship-manipulator modeling

In From et al. (2009) the classical dynamic equations for a serial manipulator arm with 1-DoF joints were extended to include the forced 6-DoF motion of the base. For more details on how to derive the dynamics see From et al. (2009) and Duindam and Stramigioli (2007, 2008). Consider the setup of Fig. 2 describing a general n-link robot manipulator arm attached to a moving base and choose an inertial coordinate frame Ψ_0, a frame Ψ_b rigidly attached to the moving base, and n frames Ψ_i (not shown) attached to each link i at its center of mass. Finally, choose a vector $q \in \mathbb{R}^n$ that describes the configuration of the n joints. Using standard notation (Murray, Li, & Sastry, 1994), the pose of each frame Ψ_i relative to Ψ_0 can be described as a homogeneous transformation matrix $g_{0i} \in SE(3)$. This pose can