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MOTION PLANNING AND CONTROL IN ROBOTICS

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ABSTRACT - In this research area, we are focused on developing control and planning algorithms for the generation of movements in autonomous robots and especially in robots with hands and legs. We develop algorithms that allow machines to move and interact with their environment in a non-trivial manner. Robots should be able to locomote on difficult terrains and manipulate objects to perform complicated tasks and in many cases they should be able to do both of these tasks at the same time. The generation and control of coordinated movements for a robot that performs several tasks at the same time is a complex problem that involves very different research areas. First, one needs to develop adequate controllers that will make sure the robots perform according to the desired plan. Then, motion generation algorithms are required to create desired motion or contact interaction policies, ideally in an optimal way.

HIGH PERFORMANCE CONTROL

Performing challenging tasks require very good controllers in order to execute desired plans. While often underestimated, carefully designed controllers can significantly increase performances by optimally exploiting the possibilities offered by modern hardware (e.g. torque actuation, high control bandwidth, multi-modal sensing). In general, we are interested in controlling very different physical quantities (positions, velocities, forces or impedance) of various robot parts (joints, end-effectors or the entire robot’s motion) to achieve several concurrent objectives. For example, while drilling a hole in a wall, it is necessary to control the drill tip position for precise drilling and interaction forces to bore the wall while at the same time the robot’s center of mass needs to be controlled for proper balancing in face of disturbances created by the manipulation task.

In order to develop high performance controllers, it is necessary to understand the physical processes underlying the actuation and the dynamics associated with the tasks the robot tries to achieve. To develop our controllers, we often use (complex or simplified) models based on rigid-body dynamics and augmented with hardware specific modeling (e.g. hydraulic dynamics for hydraulic actuated robots). The developed controllers need to be robust to uncertainties in the model estimation, computationally simple to be implemented in fast control loops and guarantee some form of optimality and robustness to disturbances.

ADAPTIVE/REACTIVE MOTIONS

Traditional motion planning generally computes a motion plan given a model of the environment and then lets the controller execute the plan. If an unexpected event happens a new plan needs to be computed using an updated model of the world, which is potentially time consuming. We are researching ways to create intermediate motion representations between the motion plan and the controller that can be used to integrate sensory information during the motion generation. In close relation with the perception for action research conducted in the department, we are investigating ways to integrate sensory feedback during the generation of movements. When unexpected events occur, the motion can then be adapted to ensure successful execution of the task. Ideally, we would like to have algorithms able to integrate task relevant sensory information at every level of planning and control. The approaches we are investigating range from model predictive control (where explicit models are required) to dynamic movement primitives with sensory feedback (where models are made implicit).

MULTI-TIME-SCALE INTEGRATION

Planning and control are often though as separate problems. We believe that tight coupling between planning and control algorithms is necessary to achieve complex tasks. The design of a controller depends on the requirement of the planned policies and conversely, the capabilities of the controller define what can be planned. For example, a controller allowing to control ground reaction forces during locomotion will allow a planner to exploit these forces to create better motion.

Such integration becomes specially relevant when generating very dynamic moves such as jumping to grasp for an out-of-reach object. We are developing methods that consider motion generation as an integrated problem where several algorithms operating at different time-scales are involved. Typically, at one end of the scale we will find fast control loops operating at the millisecond level or below, while at the other end we will find planners for symbolic reasoning operating at the seconds or minutes level. Designing algorithms for different time-scales allow to simplify the conception of these algorithms as their design can be separated. However, by requiring some coupling between them we believe that it will allow the emergence of complex behavior (i.e. behaviors more complex than the sum of each module) when interacting with the external world.

SENSOR INFORMATION INTEGRATION

We expect to see a dramatic increase of available sensors on modern robotic platform. However, we hardly know how to fully exploit the information created by available sensors on our current hardware. Usually motion planning is done with an a-priori model of the environment, without online integration of sensor information. On the other hand, control systems typically use sensor information that directly relates to the physical quantities to be controlled (e.g. collocated position or force sensors). However, very few algorithms are capable of integrating complex sensor modalities coming from active perception algorithms, nor capable of exploiting the richness of information available in these sensors to make sensible control or planning decisions. One of our research goal is to use more systematically all the sensory information available to improve motion generation and control. This research direction is done is close collaboration with the perception for action research conducted in the department.

COMPLETE SYSTEMS FOR COMPLEX BEHAVIORS

It is not sufficient to develop theoretically sound algorithms but it is mandatory to demonstrate that such algorithms, when integrated in a complete system, interact appropriately. We are therefore developing real-life complex scenarios to test the algorithms. First, we are developing a complete system for legged locomotion over rough terrain (e.g. disaster relief scenario).

Second, we are testing our algorithms within a complete system for bi-manual manipulation available in the department. Robotic experiments are not only used to validate our algorithms but also to help us understand what are the real challenges yet to be solved by our future algorithms. These developments go beyond mere motion planning and control and involve a tight integration of all the research topics developed in the department.

MOTION OPTIMIZATION

Motion generation is increasingly formalized as a large scale optimization over future outcomes of actions. For high dimensional manipulation platforms, this optimization is computationally so difficult that for a long time traditional approaches focused primarily on feasibility of the solution rather than even local optimality. Recent efforts, though, to understand this optimization problem holistically and to exploit structure in the problem to enhance computational efficiency, are starting to pay off.We now have very fast constrained optimizers that leverage second order information to enhance convergence and leverage problem geometry much more effectively than traditional planners. At the Autonomous Motion Department, we are exploring this space from many directions. One of our core efforts centers around formalizing the role of Riemannian Geometry in representing how obstacles shape the geometry of their surroundings and how those models integrate efficiently into the optimization. Our optimizers account for environmental constraints as well as behavioral terms and geometric models of the robot's surroundings while maintaining the computational efficiency needed to animate fast responsive and reactive behaviors on Apollo. Additionally, since robots can only retrieve information from the environment through limited sensors that must be processed online, no internal model of the environment will ever be sufficiently precise to act blindly. We study how our motion system can leverage the intrinsic robustness of contact controllers by explicitly optimizing a profile of desired contacts designed to reduce uncertainty. In the same way we might reach out to touch a table before picking up a glass in the dark, Apollo can localize himself efficiently through planned contact by reasoning about the trade off between uncertainty reduction and task success.

OPTIMAL CONTROL

Planning dynamic behaviors for legged robots is a challenging task because the robot is subject to strong dynamic constraints due to its floating base (i.e. it can fall). It needs to take into account intermittent contacts with the environment and apply contact forces in order to move. In this project, we address the problem of planning dynamic movements for legged robots that take into account the kino-dynamic constraints of the robot. We use optimal control techniques to find solutions that are dynamically feasible and to help synthesize feedback controllers to stabilize these plans. In particular, we are looking at the problem from three different points of view:

1. Although legged robots typically consist of many joints, we believe that most of the dynamic behavior of walking or other dynamic tasks can be explained with an underlying (simpler) dynamics model. Thus, we would like to understand what is the level of

complexity our models require in order to explain a dynamic behavior well, but at the same time serve in efficient planning and control algorithms.

2. A common planning approach on robots with invertible dynamics (e.g. a manipulator) is to generate kinematic trajectories and then in a second step invert the dynamics to generate admissible torque trajectories. However, due to the Newton-Euler equations, a floating-base robot is under-actuated. We extend kinematic planning with trajectory generation on the under-actuated part and couple the two in a common optimization framework.
3. In order to walk or climb, legged robots have to create and break contacts with the environment and apply forces at the contact support. Thus, an important part of our planning stage is finding good contact configurations leaving enough degrees of freedom to the robot for fulfilling its task.

SENSOR FUSION

When developing controllers for legged robots, one assumes that important quantities like the Center of Mass of the robot (CoM), its position and orientation in space or its joint positions and velocities are know accurately to be used in feedback laws. While the estimation of such quantities is trivial in simulation, it becomes a serious problem on real robots, especially for legged robots that can fall and are subject to unknown external disturbances. Sensors noise and biases can significantly degrade the performance of controllers. Moreover, several of these quantities cannot be measured directly (e.g. the pose and orientation in space, its CoM position or its angular momentum).

CONCLUSION

In this project, we explore the problem of fusing sensor information from inertial, position and force measurements to recover quantities fundamental for our feedback controllers. Our final goal is to find a systematic way of fusing multiple sensor modalities to improve the control of legged robots. In a theoretical part, we perform observability analysis on nonlinear estimation models to understand the fundamental limitations of our sensor fusion approaches. In our experimental work, we demonstrate that our estimators, by providing accurate estimates of important quantities, can significantly improve the effective control bandwidth and therefore the performance of our controllers. We developed state estimation methods that allow to recover the state of the floating base of a robot using information about its contact situation with improved observability characteristics. We also developed methods to estimate the CoM of the robot, its angular momentum and external wrenches applied to it by fusing kinematic, inertial and force sensing information. Finally, we explored the problem of improving velocity estimation accuracy by fusion position and inertial measurements.

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