Research Statement

Robotics Design: Supporting the Dynamic Motion of Man & Machine

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Robotics extends human performance to domains currently beyond our grasp. From assistive devices in ones hands to autonomous systems in distant lands, agile control is needed design and operate near performance bounds.

My research interest is in planning and control methods to enable dynamic motion, particularly of low-cost, compliant hardware. I look at this from both: (1) an *integrated planning and control* perspective (i.e., system → action) and (2) a *hardware design* perspective (i.e., action → system). Careful factoring and approximation (e.g., Lie group symmetries[1]) allows systems to leverage the results of large complex models/simulations adaptively during on-line operation. This provides near-optimality with speed. I explore these topics via work in three application areas: (1) iterative operations in field environments (i.e., intermittent/saturated actuation), (2) trajectories/targeting in deep brain stimulation (i.e., intermittent sensing), and (3) design and tracking of outdoor sports/rehabilitation aids for the visually-impaired.

Fundamental Research Directions

Design of Integrated Structures for Low-Cost, Compliant Robotic Systems

The increased automation of manufacturing along with increased computing performance of embedded systems makes it possible to construct and efficiently produce light-weight, low-cost sensor modules and miniature autonomous systems based on printed circuit boards[2], 3D printed structures (FDM), etc. While these technologies result in lower-cost, rapidly-producible, customizable parts, they often come at the complication of low-precision and high compliance. This poses two complementary research challenges: (1) How to adaptive control these structures, preferably in a computationally efficient manner; and (2) how to design these structures and vary their manufacturing techniques (e.g., ABS plastic compositions and material thicknesses) so as produce parts whose stiffness helps to stabilize performance.

System Reduction by Symmetry and Estimation

As systems get more complex with more and more degrees of freedom, not only do they become harder for a human to control, they become numerically intractable for a computer to optimize as well. When a system displays symmetry, and remarkably many systems do, mechanical system reduction may be employed for simplification[1]. Given that motion planning calculations are beyond exponential in their complexity; this can provide remarkable benefit in making the problem tractable. Exploiting mechanical system symmetry in integrated planning and control works to define non-holonomic constraints as a connection in the base space. That is, instead of viewing the motion planning as admissibly routing between two (or more) states, it can be viewed as removing infeasible parts of the solution space from which a solution can then be chosen. Then the problem becomes an about how to rank or optimize which section of the base space to perform subsequent actions on.

Integrated Motion Planning and Feedback Control Methods

By factoring control feasibility and parameter estimation in a unified manner, integrated planning and control methods allow for more efficient motor control and better planning in a receding-horizon sense. This occurs in domains with: (1) coupled dynamic modes, (2) many degrees of freedom, and (3) where actuator saturation is a dominant operating constraint. Such an approach provides solutions to problems that are difficult to solve explicitly by motion planning or feedback control alone as they involve both internal parameter constraints and external obstacles (e.g., an under-actuated system in an environment with obstacles – the solution requires momentum yet must avoid obstacle regions).

Hybrid optimal controls suggests the application of direct collocation methods that approximate controls by piecewise linear functions. This is then framed as a constrained optimization problem, which, in turn, can be handled numerically by large-scale SQP methods, such as SNOPT. Instead, we frame this in a motion planning context. This leads to a more explicit posing of the problem as a (policy) search. In contrast to a brute-force numerically inefficient approach, consideration of the candidate linear control law and system model allow for definition of level sets of equivalent actions (i.e., using stability verification tools, such as SOSTools or SPOT). This is then framed as a series control laws, hence giving the Gain Scheduled RRT algorithm[3].

Application Areas

Beyond “dull, dirty, and dangerous,” robotics can be seen as a means to coordinate information streams to inform better decisions. With this view, the goal is of autonomy is to reduce the complexity (degrees-of-freedom) and dynamics to better match human cognitive bandwidth. My view is that the future of robotics is rich with potential. By integrating compliant mechanisms with adaptive control, it will simply be there and do the right thing. This is manifest in a diversity of domains, some motivating applications for this research include:

Humanitarian & Outdoor Assistive Robotics

While applicable to a variety of problems, I see this work being particularly useful for informing robot hardware and system design, particularly for rescue and assistive devices. In these domains interaction has to be factored in addition to control. For example, with the Gryphon[4] humanitarian demining project, robust control provided a automatic surface tracking that allowed for a visual map of mine target location (instead a typically aural signal) along with a depth estimate (which could be computed since arm kinematics were known). This greatly informed, but did not seek to automate, the demining decision and has led to adoption of this technology.

In addition to mechanical methods (such as gravity compensation), agile robotic control can provide assistance via information fusion (i.e., sensory substitution). A recent motivating application of this is a sporting aid for children with a visual impairment[5]. Initial efforts have resulted in a programmable sporting ball with an integrated inertial sensor module that provides motion information to players via a piezo beeper. Adaptive control is needed to vary the tones so that players with low vision have a “normative” experience and be able to play alongside their fully-sighted peers as team members. To achieve this, the goal is to use statistical planning and control ideas to adaptively inform interaction by allowing systems to act in an expected (and presumably more intuitive) manner without being explicitly commanded[6].

Using Fast Motion Correction for Deep Brain Stimulation

The aforementioned Symmetry Path Correction (SPC) algorithm[1] randomly samples segments along the trajectory and then uses their condition number (relative to state variables of interest) to rank sections for correction. Unlike a regulator (that seeks to minimise error), SPC seeks to drive a system to a final destination state while respecting (internal) dynamic and (external) environmental/obstacle constraints and is well suited for compliant, dynamic systems that do not directly admit to error metrics.

Of interest is to apply this algorithm along with tissue signal signatures for “super-resolution” targeting of needle probe locations in Subthalamic nucleus Deep Brain Stimulation (DBS) procedures. While stereotactic (Leksell) frames may be used, this assumes that variations from pre-operative imaging/planning are negligible. Instead, this research seeks to use “feedback control” based on intermittent signals from the probe as it is inserted to provide better targeting. By considering locations where tissues can be classified (from microelctrode recordings and EEGs), it is possible to select segments for correction prioritized by information gain (to be exploitative) or on confidence (to be exploitative). In addition, work is considering the computation of a metric on the likelihood of deviation as such a ranking mechanism does not need to assume static properties and models. Clinical characteristics will be explored in collaboration at the UQ Asia-Pacific Centre for Neuromodulation (APCN).

Adaptive Excavation for Precision Trenching

The integrated planning and control methods are being tested using a custom designed autonomous, hydraulic excavator “robot.” Simulations and initial implementations on an excavator arm are showing strong initial results and has yielded two new control algorithms designs, including a novel approach for operation space control with complaint dynamics[7]. Digging deeper, this problem is rich with research challenges given that (1) the operation involves forces on par or greater than the weight; (2) involves a non-linear (hydraulic) plant; and (3) has coupled actuation (movement of one joint limits the others).

An interesting application for this is construction as the inefficiencies of errant digging (leave alone the costs and inconvenience of interrupted utilities) are immense. Unlike traditional robotic manipulation, excavation operates at or near the thresholds of performance. This represents a significant challenge since the motion (1) has high inertial forces; (2) is in an unstructured environment; (3) uses a highly non-linear plant; (4) has great machine-to-machine and site-to-site variation (but bucket-to-bucket structure which can be exploited); and (5) has coupled actuation. In applying integrated methods here the system can optimize coupled excavator parameter values and local similarity (hole-to-hole variation is much less than site-to-site variation) while avoiding potential obstacles that are inherently difficult to sense directly – so as to reduce the incidence of getting stuck, yet regulate forces so as not to be a brute.

References

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