Research Statement

Agile Robots: Supporting the Dynamic Motion of Machine & Man Surya P. N. Singh

From assistive rehabilitation to autonomous exploration, robotics effectively allows us to more consistently explore smarter and farther. To realize this requires designing agile systems – as efficient and fluid operation implies driving near performance bounds.

My research interests are in synthesizing dynamic motion. I look at this from both: (1) an *integrated planning and control* perspective (i.e., model → action) and (2) a *system identification and reduction* perspective (i.e., action → model).

Of course, no model is perfect. Abstraction is engineering. The goal is to know where the boundaries lie. Careful model factoring and approximation (using Lie group symmetries and Calculus of Variations) allows systems to leverage the results of large complex models/simulations (that are generally pre-computed off-line) adaptively during on-line operation. This provides near-optimality with speed. This is currently motivated by two applications: motion tracking and optimization for (1) optimizing mineral extraction operations and (2) for trajectories in gymnastics and diving.

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. The utility of this approach is evident in domains with: (1) coupled dynamic modes, (2) many degrees of freedom (e.g., a standard human walking model has 23-dof), 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., consider a 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. This approach (for example as implemented in PROPT) yields impressive open-loop control paths to non-linear problems. However, this has limitations. First, because the solution is a path, further processing (such as gain scheduling) is required to return a set of feedback control laws, which give disturbance rejection. Second, these methods do not scale well. Third, they require a good (analytic) model for calculating the Jacobians and Hamoltonians efficiently.

At the moment, this method is being investigated for assisting with heavy manipulation tasks, such as those found in lifting heavy loads (e.g., shoveling). The research leverages 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.

Moving on, 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. The inefficiencies of errant digging (leave alone the costs and inconvenience of interrupted utilities) are immense. While excavation might seem ordinary (a robot arm on tracks as it were), it is complicated. Unlike traditional robotic manipulation, excavation operates at or near the thresholds of performance. It represents a significant research challenge as the operation (1) has high inertial forces (on the order of the weight of the machine if not greater); (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 significant bucket-to-bucket structure which needs to be exploited); and (5) has coupled actuators (movement of one joint affects movement of the others). 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.

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. 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.

This theory can be manifest in various application domains. Of particular interest is human tracking outdoors. IR-camera based motion capture can not be used due the lack of structure and sunlight intensity. Inertial data (from shoes) alone is not sufficient due to drift. A hybrid solution is to augment vision with inertial sensors placed at important landmarks. Together this provides a means for gathering scientifically interesting data on this complex motion, which is central to better training and performance.

Of course while one can "optimize" torques for a motion, with a person there is no analogue to "downloading" commands! Due to this, this effort is initiating study in the form of better training aids (or more generally in human-robot interaction) so as to impart the suggestions from optimizations based on the models identified from initially observed data.

Future Directions

Future efforts are considering approaches that require less exact models; that is, to frame this as a regression of the policy space. How to do this well, particularly for subsequent motion planning tasks, is very much an open research question.

While applicable to a swath 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 and speed are paramount over complete autonomy. For example, with the Gryphon 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 keeping with this, I seek 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. Consider, for example, navigating around spilled coffee. Trying to sense and program for this (and related contingencies) is incredibly difficult, yet, as we have shown in recently accepted work, following the cues of people walking around it is relatively much easier. Utilizing this is a new, but important, step for agile field robotics.

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.