Control Methods for Coordinated, Multi-Arm Manipulation with Soft Robots

by

Dustan Kraus

A prospectus submitted to the faculty of
Department of Mechanical Engineering
Brigham Young University

April 15, 2017

Prospectus Approval

Prospectus submitted by:

Dustan Kraus — Date

This prospectus has been approved by each member of the Graduate Committee:

Marc Killpack - Chair — Date

Mark Colton — Date

Randy Beard — Date

1 Problem Statement

Every year, the number of robots manufactured increases. Robots play a role in the production of most things we use on a day to day basis; however, despite this trend, we have yet to see robots play a more personal role in our daily lives.

Industrial robots, though highly precise and capable, have a relatively high inertia and are heavily geared. This severely limits how quickly and safely they can move while operating in close proximity to humans to avoid unexpected collisions and high impact forces.

Development of soft, lightweight robots that are inherently safe around humans will enable robots to play a much more personal role in our lives. Imagine a robot that could gently help a disabled person into their wheelchair, lift a survivor to safety in a disaster scenario, or even work alongside an astronaut in space. Tasks such as these are difficult, if not impossible, with only one arm. My objective is to develop and implement control algorithms for multi-arm manipulation on soft, pneumatically actuated robots (like the one shown in Figure 1).

Figure 1: A five degree of freedom soft robot provided by Pneubotics

2 Background

Multi-arm manipulation does not have a specific agreed-upon definition. It could be many fingers on a hand manipulating a small object, or many arms manipulating a large object. In fact, both of these scenarios could use the same control principles. Furthermore, multi-arm manipulation can be categorized by un-coordinated and coordinated tasks. Un-coordinated manipulation tasks are those in which the arms are performing tasks that do not require interaction (e.g. one arm is moving parts while a second arm is performing an unrelated assembly task). Jobs which require two or more robotic arms to physically interact with the same object are classified as coordinated manipulation tasks. [1] My research will be focused on coordinated, multi-arm manipulation tasks.

One difficulty in coordinated, multi-arm manipulation with traditional robots is that small deviations in end effector position or orientation from any of the arms while holding a rigid object can result in large stresses on both the object and internally on the arm. To compensate, many researchers have proposed hybrid force/position control schemes which seek to control the position of an object being grasped by several manipulators while either keeping the forces below a certain threshold or maintaining a certain force. [2, 3, 4, 5, 6, 7] A challenge with this approach is the coordination of high bandwidth centralized controllers.

Additionally, if the software or hardware malfunctions and the force control stops working, traditional robots could exert a dangerous amount of force on the object being manipulated, themselves, humans, or other delicate equipment nearby.

An alternative and novel approach is to mitigate buildup of high forces by using a robot with flexible links and passive compliance in the joints from the compressibility of air. Because soft robots are inherently compliant, deviations in object position result in significantly lower buildup of forces; thus, they lend themselves nicely to tasks involving several arms. Even tasks with one rigid arm and multiple soft arms become simpler as the whole system is forgiving of end effector deviations due to compliance of the soft arms. Therefore, one of the major concerns with successful implementation of coordinated, multi-arm manipulation is eliminated. Additionally, because these robots are soft and inherently compliant, they are very safe around humans and delicate equipment even if something malfunctions. On the other hand, compliant links and joints introduce new challenges (addressed below) into the control paradigm, and currently do not perform as well as state of the art torque controlled robots like Robonaut 2.

Do more literature review and include it here.

3 Research Objectives

I propose that coordinated multi-arm manipulation can realistically be implemented with inflatable, pneumatically actuated robots. My goals are to implement coordinated multi-arm control for (1) accurate manipulation of rigid objects in free space, (2) impact tasks with rigid objects (like sweeping off a solar panel or assembly of construction materials that require impact for insertion), and (3) soft object manipulation tasks (like moving a tarp or a flexible solar array). Here are the underlying questions to address:

- Two key challenges with soft robots are accuracy and repeatability. The dynamics of the arms can change with a variety of different stimuli such as temperature change, pressure loss through bladder punctures, and actuation hysteresis. Additionally, the bladders often reseat themselves as the arms move. What type of control scheme will result in the highest task space accuracy and repeatability?

- Which type of control scheme will be most effective in coordinated manipulation tasks for soft robots?

To answer these research questions, there are many intermediate steps described in the following section.

4 Proposed Research

Manipulability Improvements: Recent design changes have left the robot in Figure 1 (King Louie) with only four degrees of freedom per arm. To perform general manipulation tasks, each end effector needs to be controllable in at least six degrees of freedom. Furthermore, I recently finished simulating King Louie's reachable workspace (using current DH parameters and forward kinematics) and found that with his current configuration, the volume reachable by both arms is 0 (see Figure 2).

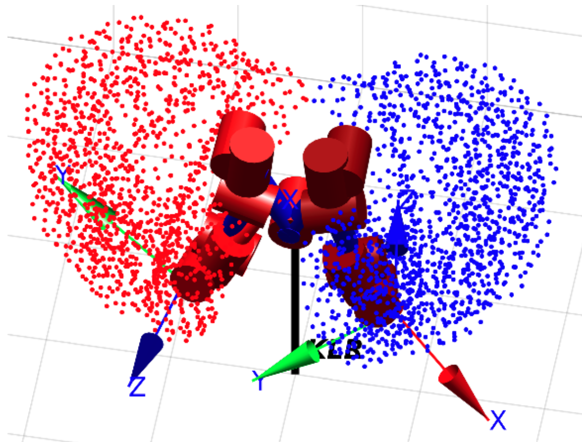

Figure 2: This is a visualization of the current workspace of each of King Louie's arms. The left arm workspace is red, while the right is blue.

Another student in my research group recently submitted a paper to ICRA 2017 on rigorous design optimization of soft robots.

figure out if this paper has been accepted, and cite it

I will build on this work in designing an optimization to select which degrees of freedom to add and how to mount the arms to allow for coordinated manipulation tasks. Undergraduate researchers in the lab have designed a way to both mount the arms to a new surface and attach additional degrees of freedom. I will use this mounting technique to implement the results of my optimization, so that I can perform multi-arm manipulation tasks.

Single Arm Hybrid Controller Development: Task space accuracy and repeatability are affected by dynamic and kinematic modeling error (accurately modeling King Louie and other soft robots is not trivial). Previous researchers in the RaD Lab have designed an algorithm using model predictive control (MPC) that can command a single arm in joint space. [8] I have used inverse kinematics libraries like TRAC-IK in the Robot Operating Systemto compute desired joint angles for this controller; however, this control method alone does not result in accurate task space positions and orientations due to dynamic and kinematic modeling error. A common control technique to close error is visual servoing. [9][10] My first approach to this problem was to create a hybrid controller using an HTC Vive virtual reality system. The Vive uses two IR cameras to report the position and orientation of targets which I used for servoing feedback to close the end effector position error and improve repeatability. This method is currently very slow, and uses the Vive coordinate frames rather than motion capture frames where the robot's DH parameters were defined. I will work on tuning the controller, and optimizing the code to speed it up, and have been working on an optimization to relate the two coordinate frames.

Coordinated, Multi-Arm Controller Development: My first coordinated multi-arm manipulation approach will be to design and implement an object level model predictive controller. MPC uses a system's dynamics to predict the control inputs that will result in desired system motion over a short time horizon. In this case, the system is the object, and there are n robotic manipulators grasping the object in 3D space as shown in Figure 3.

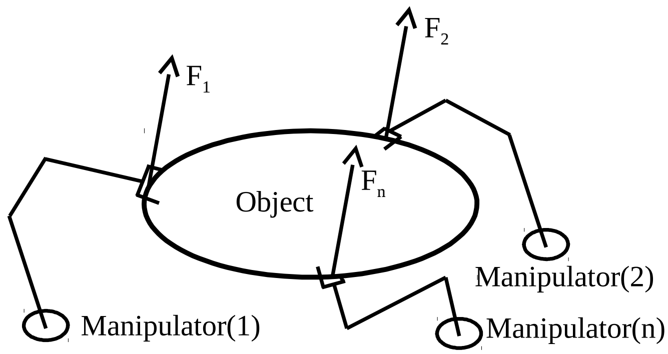

Figure 3: This shows a figure being manipulated by n robotic manipulators.

The control inputs output by MPC are forces and torques to be applied to the object by each manipulator grasping the object. Initially, I will assume that I know the dynamics of the object (by using objects that I can easily calculate the inertia of, like a block). Another student in my research group has researched estimating the dynamics of an unknown object. I will build on this research to estimate dynamic models for the various objects I will manipulate. These models will likely have error, but previous research with MPC has found it to be robust to modeling error (even with plus or minus half of nominal mass values). [11][12] My proposed control scheme is of the form shown in Figure 4.

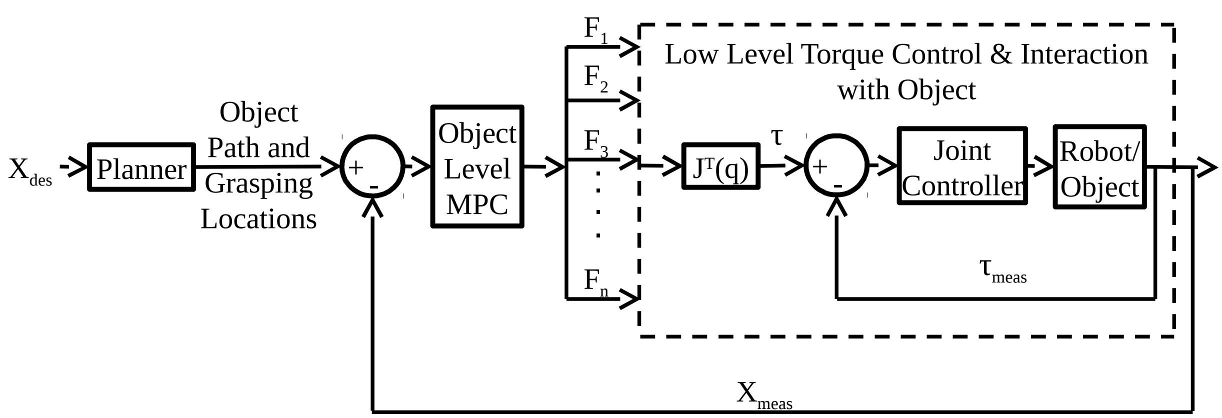

Figure 4: This figure shows the proposed object level MPC control scheme.

X_{des} and X_{meas} are desired and measured end effector position and orientation, F_1 to F_n are wrenches at the end effector of each arm which are fed into a low level joint torque controller, J is the Jacobian of each arm, and τ and τ_{meas} are the required and measured joint torques. I will design this controller to be very modular. The first module to develop will be the Object Level MPC block. I have already derived the dynamic equations for an object in 3D space with n forces and torques applied to the object. This module will calculate the desired wrenches to be applied to the object given a desired and current location/trajectory as well as the object dynamics. The next module will be the robotic manipulator control. To design this module, I will need to figure out the best control scheme to achieve the desired wrenches at the end of each manipulator. The final module is the planning module. The long term goal of this module is twofold. First, the module will need to compute optimal grasping locations for each end effector. I suspect that these locations will be determined by the robot kinematics as well as the weight distribution and desired configuration of the object. Second, given grasping locations for each end effector, the module will need to compute a desired trajectory for each end effector. This path must be constrained to object motion that is possible given the force/torque and kinematic constraints of the robot manipulators. A student in the RaD lab has already worked extensively on this problem for a single arm, and I will build on his work.

Once I can accurately and repeatably manipulate objects using the two arms on the robot in Figure 1, I will expand my research to utilize more soft arms and even a more traditional torque controlled Baxter Research Robot Arm. This will demonstrate the applicability of my algorithms to systems that include multiple soft robots and a rigid robot.

5 Anticipated Contributions

My anticipated timetable for publications is included below in table 1.

Co-submit work on servoing and coordinate frame transformation optimization to robotics journal	May 2017
Submit conference paper on object level mpc with two arms given grasping locations, object model, and desired object path to the International Conference on Robotics and Automation 2018 (ICRA 2018). At this point the planning module will not have been developed.	September 2017
Submit conference paper on planning module (computing grasping locations and path) to the International Conference on Intelligent Robots and Systems 2018 (IROS 2018)	March 2018
Submit to robotics journals on full system (planning module, as well as object level mpc)	April 2018

Table 1: This table contains the anticipated publications that will result from my proposed project.

References

[1] C. Smith, Y. Karayiannidis, L. Nalpantidis, X. Gratal, P. Qi, D. V. Dimarogonas, and D. Kragic, “Dual arm manipulationA survey,” *Robotics and Autonomous Systems*, vol. 60, no. 10, pp. 1340–1353, 2012.

[2] S. Sakaino, T. Sato, and K. Ohnishi, “Precise Position/Force Hybrid Control With Modal Mass Decoupling and Bilateral Communication Between Different Structures,” *IEEE Transactions on Industrial Informatics*, vol. 7, no. 2, pp. 266–276, may 2011. [Online]. Available: http://ieeexplore.ieee.org/document/5738705/

[3] T. Alberts and D. Soloway, “Force control of a multi-arm robot system,” in *Proceedings. 1988 IEEE International Conference on Robotics and Automation.* IEEE Comput. Soc. Press, 1988, pp. 1490–1496. [Online]. Available: http://ieeexplore.ieee.org/document/12278/

[4] S. Hayati, “Hybrid position/Force control of multi-arm cooperating robots,” in *Proceedings. 1986 IEEE International Conference on Robotics and Automation*, vol. 3. Institute of Electrical and Electronics Engineers, 1986, pp. 82–89. [Online]. Available: http://ieeexplore.ieee.org/document/1087650/

[5] T. Yoshikawa and X.-Z. Zheng, “Coordinated Dynamic Hybrid Position/Force Control for Multiple Robot Manipulators Handling One Constrained Object,” *The International Journal of Robotics Research*, vol. 12, no. 3, pp. 219–230, jun 1993. [Online]. Available: http://ijr.sagepub.com/cgi/doi/10.1177/027836499301200302

[6] M. Uchiyama and P. Dauchez, “A symmetric hybrid position/force control scheme for the coordination of two robots,” in *Proceedings. 1988 IEEE International Conference on Robotics and Automation.* IEEE Comput. Soc. Press, 1988, pp. 350–356. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=12073

[7] C. Derventzis and E. Davison, “Robust motion/force control of cooperative multi-arm systems,” in *Robotics and Automation, 1992. Proceedings., 1992 IEEE International Conference on.* IEEE, 1992, pp. 2230–2237.

[8] C. M. Best, M. T. Gillespie, P. Hyatt, L. Rupert, V. Sherrod, and M. D. Killpack, “A new soft robot control method: Using model predictive control for a pneumatically actuated humanoid,” *IEEE Robotics & Automation Magazine*, vol. 23, no. 3, pp. 75–84, 2016.

[9] H. Wang, B. Yang, Y. Liu, W. Chen, X. Liang, and R. Pfeifer, “Visual Servoing of Soft Robot Manipulator in Constrained Environments with an Adaptive Controller,” *IEEE/ASME Transactions on Mechatronics*, pp. 1–1, 2016. [Online]. Available: http://ieeexplore.ieee.org/document/7575727/

[10] N. Vahrenkamp, C. Böge, K. Welke, T. Asfour, J. Walter, and R. Dillmann, “Visual servoing for dual arm motions on a humanoid robot,” *9th IEEE-RAS International Conference on Humanoid Robots, HUMANOIDS09*, pp. 208–214, 2009.

[11] M. D. Killpack and C. C. Kemp, "Fast reaching in clutter while regulating forces using model predictive control," in *Humanoid Robots (Humanoids), 2013 13th IEEE-RAS International Conference on*. IEEE, 2013, pp. 146–153.

[12] M. D. Killpack, "Model predictive control with haptic feedback for robot manipulation in cluttered scenarios," Ph.D. dissertation, Georgia Institute of Technology, 2013.