Physical Human Interaction for an Inflatable Manipulator

Siddharth Sanan, Mike Ornstein and Christopher G. Atkeson

***Abstract*— There is a growing need for robots that can function in close proximity to human beings and also physically interact with them safely. We believe inherent safety is extremely important for robots in human environments. Towards this end, we are exploring the use of inflatable structures for manipulators instead of traditional rigid structures, to improve safety in physical human robot interaction (pHRI). This paper develops a contact detection and reaction scheme for an inflatable manipulator prototype. The resulting scheme is used for physical interaction tasks with humans. Experiments verifying the efficacy of the contact detection scheme are shown using two interaction scenarios.**

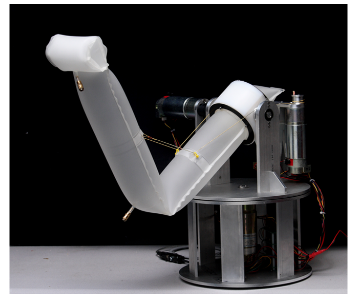


Fig. 1. Current prototype of multi DoF inflatable arm

I. Introduction

If a robot is to function in an environment which is shared by humans and interact with humans safely, the risk of physical injury to humans during its operation must be minimized. In industrial applications, robots have functioned in an isolated workspace which human workers are prohibited to enter due to safety protocols. Such protocols are not a suitable solution for domestic robots, instead they must be inherently safe. Inherent safety means that the robot has physical properties which make it unlikely to cause physical harm. This is particularly important due to unpredictable behavior resulting from computer crashes, sensor failures and an unstructured environment. We believe inflatable structures offer a promising solution for inherent safety.

There are a number of issues concerned with safety in robotic systems [1], [2]. One of the main concerns is safety under uncontrolled impacts. Other issues include, but are not limited to, injury due to quasi-static loading and lacerations due to sharp contact. We hope to address injury risks due to uncontrolled impacts by using inflatable structures.

Impact safety in a system can be improved by reducing the reflected inertia on the contact side of the impact and by reducing the interface stiffness at the contact location. The distributed macro-mini actuation approach (DM^2) [3] intelligently distributes mass and stiffness across the joints to reduce reflected inertia of the system; while the DLR arm [4] uses a lightweight design to improve safety. [5] introduces a velocity dependent stiffness between the actuator and the link to improve safety at various speeds of operation; while [6] utilizes a soft covering. It must be noted that simply limiting the joint velocity of traditional rigid link robots will allow satisfaction of impact safety constraints, however the velocity limits imposed would cause the robot to be impractically slow. As noted in [5], it is this safety-performance tradeoff that drives design of robots for close interaction with humans. Inflatable robots can, as mentioned before, be extremely lightweight and have passive compliance. This can lead to an extremely low reflected inertia during impacts and therefore a high level of inherent safety.

Inflatable structures were utilized in prior work by our group [7] to develop a prototype single-link inflatable arm, and force control methods for it. There have been other prior attempts to utilize inflatable structures in robot manipulators. Most notably in the early 1980's, [8] built a manipulator consisting of a single inflatable link with pneumatic actuators along its length that caused bending of the link in multiple directions. [9] appended a traditional rigid robot manipulator (PUMA) with an inflatable link at the distal end and presented an analysis of this system. These efforts suggest the applicability of inflatable structures for robot manipulators, however considerable research into such systems is still needed in order for such systems to gain wide acceptability as a viable technology for operation in human environments. In this paper, we develop new interaction capabilities for our multi-DoF inflatable manipulator (Fig. 1) recently designed by our group [10].

This paper is organized as follows. Sec. II provides a description of the design of the two link inflatable manipulator. Sec. III describes a joint angle estimation method for inflatable joints. Using this joint angle estimation, a contact detection scheme is described in Sec. IV along with experiments on the real robot to verify its ability to detect contact. Reaction schemes, using contact detection, are developed to handle unintended and intended physical interactions in Sec. V. Conclusion and future work are presented in Sec. VI.

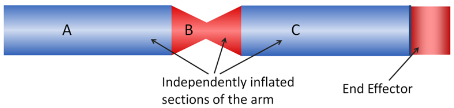
II. The Inflatable Manipulator

The inflatable manipulator (Fig. 1) is built using membrane material (polyurethane film: Catalogue #3460, McMaster-

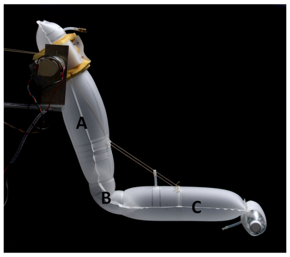
This material is based upon work supported in part by the National Science Foundation under grants EEC-0540865 and ECS-0824077

S. Sanan and C.G. Atkeson are with the Robotics Institute, Carnegie Mellon University, Pittsburgh, PA, USA (sanan@cmu.edu, cga@cmu.edu)

Mike Ornstein is with the Dept. of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA, USA (mornstein@cmu.edu)



(a) Arm structure schematic (top view)



(b) Physical arm (side view)

Fig. 2. Schematic of the arm structure and the physical arm with independently inflated links (A and C) and the joint (B).

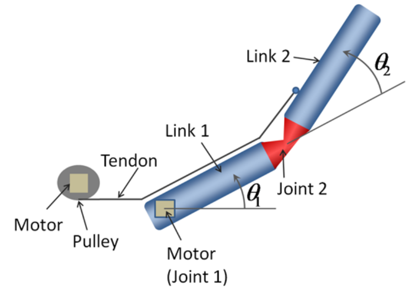


Fig. 3. Manipulator schematic showing actuation setup for the arm

Carr) which is maintained under tension by the use of pressurized air. This leads to an extremely lightweight structure which has a weight of the order of a few grams (≈ 5 gms). Furthermore, it allows for a low contact stiffness providing a soft contact interface throughout the structure. In addition, the inflatable structure allows for structural compliance in the form of link flexibility due to the relatively low Young's modulus of polyurethane (≈ 0.025 GPa) used in its construction when compared to traditional materials such as aluminum (≈ 69 GPa) and steel (≈ 200 GPa). The above features are all highly desirable in a manipulator to be inherently safe for operation in human environments.

We will briefly describe the construction of the manipulator next.

A. The Arm

The arm (schematic shown in Fig. 2a) consists of pneumatically sealed inflatable beams which function like traditional links. These links (sections A and C) are connected to each other in a serial manner via another pneumatically sealed section (section B) which functions as a joint between the links. Section B has a reduced cross-section at a particular location. This makes its behavior similar to that of a flexure joint often utilized in compliant mechanisms [11] as it behaves like a revolute joint with a torsional spring. In addition to the links and the joint, the arm is also equipped with an inflatable gripper, which we call the Inflatable Torus, that serves as the end effector of the manipulator. The Inflatable Torus is passively connected to the rest of the arm structure using a thermally welded seam.

B. Actuation

The inflatable manipulator in its current form has two active degrees of freedom. The first link (section A in Fig. 2a) is actuated by directly coupling it to a DC servo motor. The second link (section C in Fig. 2a) is actuated using tendons which are driven by DC servo motors as shown in the schematic in Fig. 3. We have also explored other actuation schemes such as McKibben actuators.

III. Inflatable Joint Angle Estimation

It is possible to derive a simple map between the motor shaft angle (θ_{2m}) and the inflatable joint angle θ_2 under the assumption that the tendon is taut [10], we shall refer to this map as the transmission map, $T : \theta_{2m} \mapsto \theta_2$. Since the tendons are pull only, i.e. compressive loads cannot be supported, loads that have a positive moment about joint 2 will cause deflection of link 2 based on the stiffness of the joint. This deflection is not resisted by the tendon causing it to slack. A joint angle estimation method that is not dependent on the tendon transmission kinematics is therefore useful.

It is observed that the pressure (P_J) in the joint varies with the joint angle θ_2. It is therefore possible to estimate the joint angle θ_2 by measuring the pressure P_J in the inflatable joint 2. We shall refer to this estimate as the pressure model joint angle, θ_2^P. A pressure sensor (Freescale MPXV5100GC6U) connected to the joint via a tube was utilized to measure the pressure P_J. Data shown in Fig. 4 was collected by driving the joint to various angles. A cubic polynomial was fit to the data, resulting in the model $\theta_2^P = z(P_J)$ for predicting the joint angle θ_2 using the pressure measurement P_J. From the experimental data, it was observed that a resolution of $\approx 5^\circ$ can be achieved for θ_2 estimated using pressure measurements.

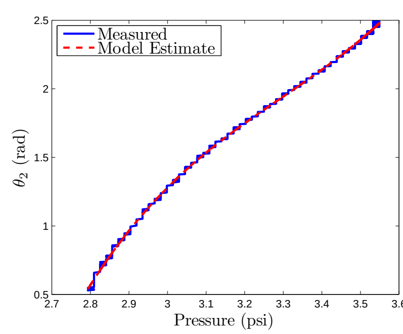


Fig. 4. Joint pressure (P_J), joint angle (θ_2) data and joint angle prediction using fit model.

The identified model can be utilized in a contact detection scheme, we will describe the working of such a scheme next.

IV. Contact Detection

It is possible to detect contact with an external object when the contact location is on the second link of the manipulator. This is done by comparing the angle estimate from the transmission map (θ_2^T)and the pressure model (θ_2^P) to generate a boolean contact variable (α), given by:

$$\alpha = \begin{cases} 1, & \text{if } \left(\theta_2^T - \theta_2^P\right) > \varepsilon_{th} \\ 0, & \text{if } \left(\theta_2^T - \theta_2^P\right) \leq \varepsilon_{th} \end{cases} \tag{1}$$

where, $\alpha = 1$ indicates contact has occurred while $\alpha = 0$ indicates no contact, $\theta_2^T = T(\theta_{2m})$ and $\theta_2^P = z(P_J)$. Fig. 5 shows the evolution of the kinematic and pressure model joint angle estimate along with the generated contact variable for a particular trial. The detection scheme successfully infers contact (the time period when $\alpha = 1$) with an external agent. The threshold ε_{th} can be used to control the sensitivity of the detection scheme. Typically, its value is chosen to be close to the obtainable resolution for the joint angle using the pressure model.

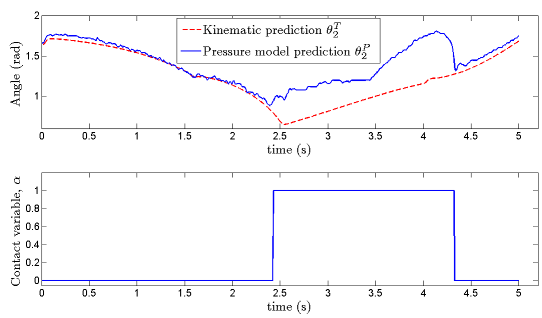


Fig. 5. Kinematic and pressure model joint angle estimates are shown during a trial. When contact occurs, the discrepancy between the two increases causing the contact variable to become true.

V. Reaction Schemes

A reaction scheme coupled with the above contact detection scheme can be used to generate a variety of behavior for the inflatable manipulator. For instance, the reaction scheme can be used to minimize unintended interactions between the manipulator and an external agent by causing the manipulator to move away from the external agent once contact is detected. In other cases when interaction is intended, such as for sponging, the reaction scheme can also be used to execute a wiping motion upon detecting contact. We will next describe these two reactions schemes as implemented on the inflatable manipulator.

A. Unintended Interaction

As mentioned above, the reaction scheme may be used to minimize unintended interactions. Such a reaction scheme is useful, for instance, when the manipulator is following a trajectory and an unobserved external agent enters the path of the manipulator. For this reaction scheme, the contact detection scheme must initiate motion of the manipulator away from the external agent, when contact is detected. Fig. 6 shows the typical operation of the manipulator using such a reaction scheme.

Fig. 7 shows the contact forces occurring with the above reaction scheme implemented on the inflatable manipulator.

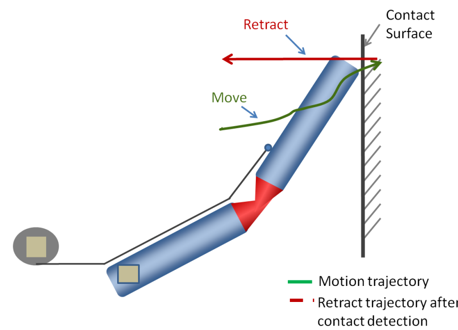


Fig. 6. Schematic showing typical motion of the end effector for the reaction scheme to handle unintended interactions.

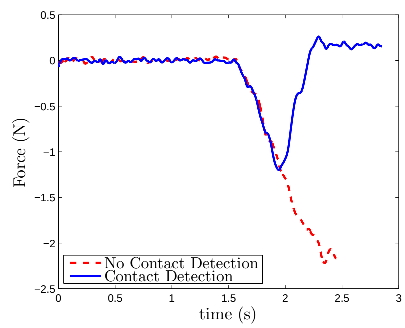


Fig. 7. Contact forces with and without the contact detection scheme. When the contact detection scheme is not employed, the robot continues to follow its desired task space path. In the presence of contact detection, the manipulator stops following its desired task space path and instead retracts from the external agent.

A flat surface instrumented with a force/torque sensor was used to obstruct the path of the manipulator. Fig. 8a shows the motion of the manipulator under this reaction scheme when contact occurs with a human.

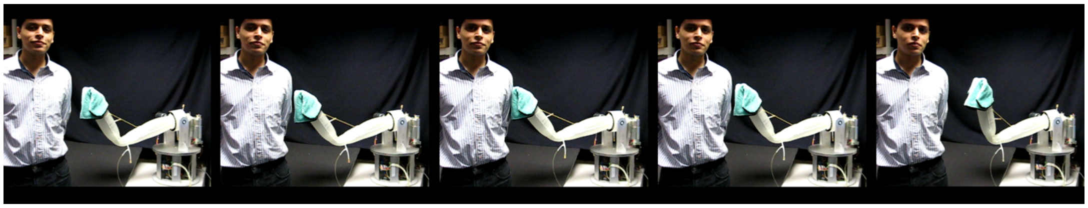
B. Intended Interaction - Sponging

For a simplified sponging task, the contact detection scheme is used to switch between two motion primitives: 1) Approach and 2) Wipe. The approach primitive essentially prescribes an end effector motion to seek contact with an external object. The wipe motion assumes the contact surface is vertical and prescribes a vertical motion for the end effector. Fig. 9 shows the typical motion of the end effector when contact occurs. Although the inflatable manipulator, at this stage, does not have additional perception capabilities (such as vision), these can be added to better guide the approach motion primitive. The move and lift primitives are additional primitives to handle the start and end of the task execution.

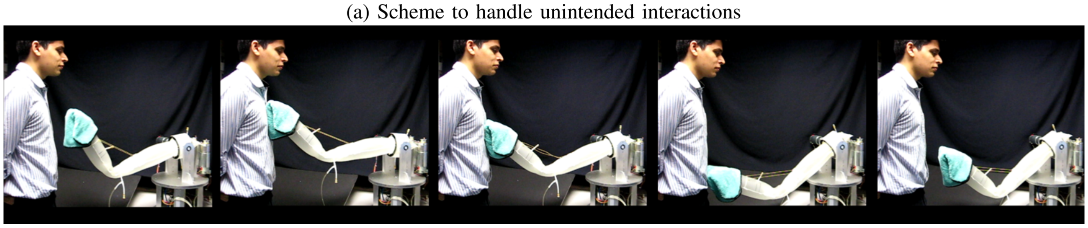
Using the above contact detection and reaction scheme, the sponging task was performed on a flat surface instrumented with a force sensor to measure contact forces. The measured contact forces during the task are shown in Fig. 10.

VI. Conclusion and Future Work

A contact detection and reaction scheme for an inflatable manipulator, enabling safe physical human interaction,



(a) Scheme to handle unintended interactions



(b) Scheme to handle intended interaction during a simplified sponging task.

Fig. 8. Motion of the manipulator under two reaction schemes for unintended and intended interactions

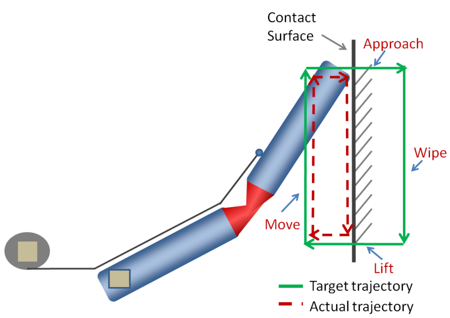


Fig. 9. Schematic showing typical motion of the end effector for the sponging task.

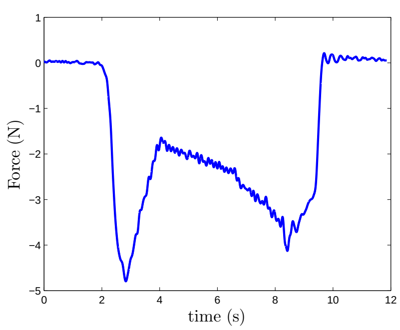


Fig. 10. Contact force during the sponging task using the contact detection scheme.

are presented. The contact detection scheme uses pressure sensing at the inflatable joint to infer contact. Trials using the inflatable manipulator prototype indicate that the contact detection scheme can successfully detect contact. Using the reaction strategy for unintended interactions, the measured contact forces show that the manipulator is capable of very safe physical interaction with humans. For intended interactions, an alternate reaction strategy is also presented, wherein sponging action is performed once contact is detected.

The contact detection scheme, presented in this paper, will be appended with more sensors in the future, such as tendon load sensors and joint torque sensors. This will allow us to extend contact detection to locations on link 1 and also detect out-of-plane (lateral) contacts. Additionally, visual perception will be added to the system to better inform the reaction strategies. The developed contact detection scheme will be used within a larger framework for compliant control, to robustly carry out tasks involving close physical human robot interaction.

References

[1] S. Haddadin, A. Albu-Schaffer, and G. Hirzinger, "Requirements for Safe Robots: Measurements, Analysis and New Insights," *The International Journal of Robotics Research*, vol. 28, no. 11-12, pp. 1507–1527, 2009.

[2] A. De Santis, B. Siciliano, A. De Luca, and A. Bicchi, "An atlas of physical human–robot interaction," *Mechanism and Machine Theory*, vol. 43, no. 3, pp. 253–270, 2008.

[3] M. Zinn, O. Khatib, and B. Roth, "A new actuation approach for human friendly robot design," in *Proc. 2004 IEEE Int. Conf. Robot. Autom. (ICRA)*, vol. 1, April-1 May 2004, pp. 249–254.

[4] G. Hirzinger, A. Albu-Schaffer, M. Hahnle, I. Schaefer, and N. Sporer, "On a new generation of torque controlled light-weight robots," in *Proc. 2001 IEEE Int. Conf. Robot. Autom. (ICRA)*, vol. 4, 2001, pp. 3356–3363.

[5] A. Bicchi and G. Tonietti, "Fast and soft-arm tactics," *IEEE Robot. Autom. Mag.*, vol. 11, no. 2, pp. 22–33, 2004.

[6] T. Mukai, M. Onishi, T. Odashima, S. Hirano, and Z. Luo, "Development of the tactile sensor system of a human-interactive robot ri-man," *IEEE. Trans. Robot.*, vol. 24, no. 2, pp. 505–512, April 2008.

[7] S. Sanan, J. Moidel, and C. Atkeson, "Robots with Inflatable Links," in *IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2009*, 2009, pp. 4331–4336.

[8] R. Baldur and W. Blach, *Inflatable manipulator*. Society of Manufacturing Engineers, 1985.

[9] N. Salomonski, M. Shoham, and G. Grossman, "Light robot arm based on inflatable structure," *CIRP Annals-Manufacturing Technology*, vol. 44, no. 1, pp. 87–90, 1995.

[10] S. Sanan, M. Ornstein, and C. Atkeson, "An inflatable manipulator for safe physical human interaction," in *IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2011*, 2011.

[11] L. Howell and A. Midha, "A method for the design of compliant mechanisms with small-length flexural pivots," *Journal of Mechanical Design*, vol. 116, p. 280, 1994.