Hysteresis Dehunting of a Tendon-Sheath Confined Space Manipulator for Fast and Precise Control

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Contribution

The main contributions of this work are to (1) develop an automation method that converges each joint to target values while avoiding backlash and stick slip friction and (2) apply the automation method in a traded control scheme to dehunt the teleoperation. Experimental results show that the approach leads to an end effector precision of five-thousands of an inch, over an order of magnitude higher compared to other works.

Introduction

Confined space manufacturing and maintenance is common in aerospace and naval industries, where a mechanic enters hazardous conditions to perform their work. Robots that can be installed from outside without entering the confined space enable teleoperation in a hazard-free manner. One such confined space - aircraft wing tanks - contain volatile fumes, either fuel for in-service aircraft, or sealant during manufacturing. Such environments have potentially ignitable vapors and require certified electronics. This makes traditional robotic solutions challenging to implement. Tendon-sheath actuated robotic manipulators offer an intrinsically safe design by relocating motors outside of the confined space, as well as allowing for reduced size and weight.

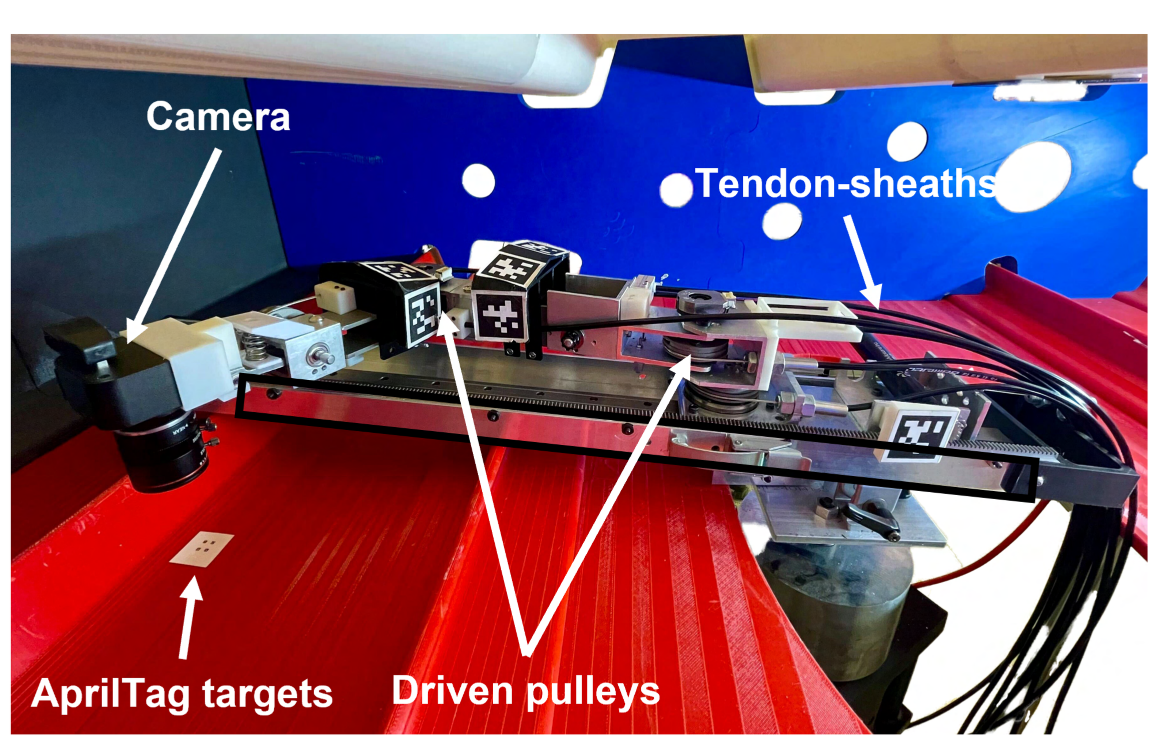


Figure: Manipulator arm inside of 3D printed tank mock-up.

Backlash Inverse Approach

The uncompensated control scheme incorporates backlash compensation for each joint using the smooth backlash inverse. Overshooting the target due to too large of a modeled discontinuity could lead to hunting, so it is specified in as less than the modeled backlash dead zone. While this aids in compensating for the backlash, the adverse effects of the backlash repeatability error and the stick slip friction position error are still present.

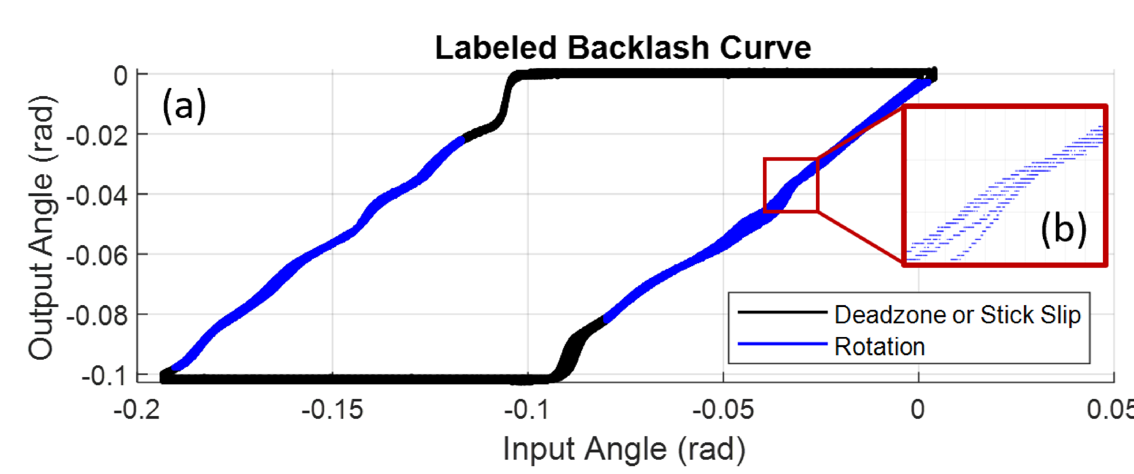


Figure: Backlash curve (a), magnified showing variation (b)

The standard backlash inverse approach is applied using a visual servo to align with predefined AprilTag locations. In teleoperation, the user gives velocity commands in the camera frame using the inverse Jacobian. The AprilTag alignment task mimics precision manufacturing tasks such as drilling.

Monotonic Control Approach

Accounting for the backlash repeatability error and stick slip friction, the inverse automation is built upon such that each joint reaches the target by first *backtracking*. Backtracking configures the initial joint position such that each joint can reach the target without overshooting. When going to a target the controller will first ensure that the initial joint position error, $e_i(0)$, is larger than the combined maximum potential backlash and stick slip friction step. The joint is commanded a large constant velocity in the opposite direction of the desired angle, $\theta_{i,d}$, until

$$|e_i(0)| > \bar{e}_{i,b} + \bar{e}_{i,f}. \tag{1}$$

Where $\bar{e}_{i,b}$ and $\bar{e}_{i,f}$ are upper bounds on backlash error and stick slip derived from experimental data. The bounds ensure all joints are out of backlash and any step subsequently induced from the stick slip friction will not cause θ_i to overshoot $\theta_{i,d}$.
In automation, the method is applied directly using a visual servo. Teleoperation uses traded control. Intent inference determines the user's desired goal from joystick inputs, and user can press a controller button to engage compensated automation.

System Overview

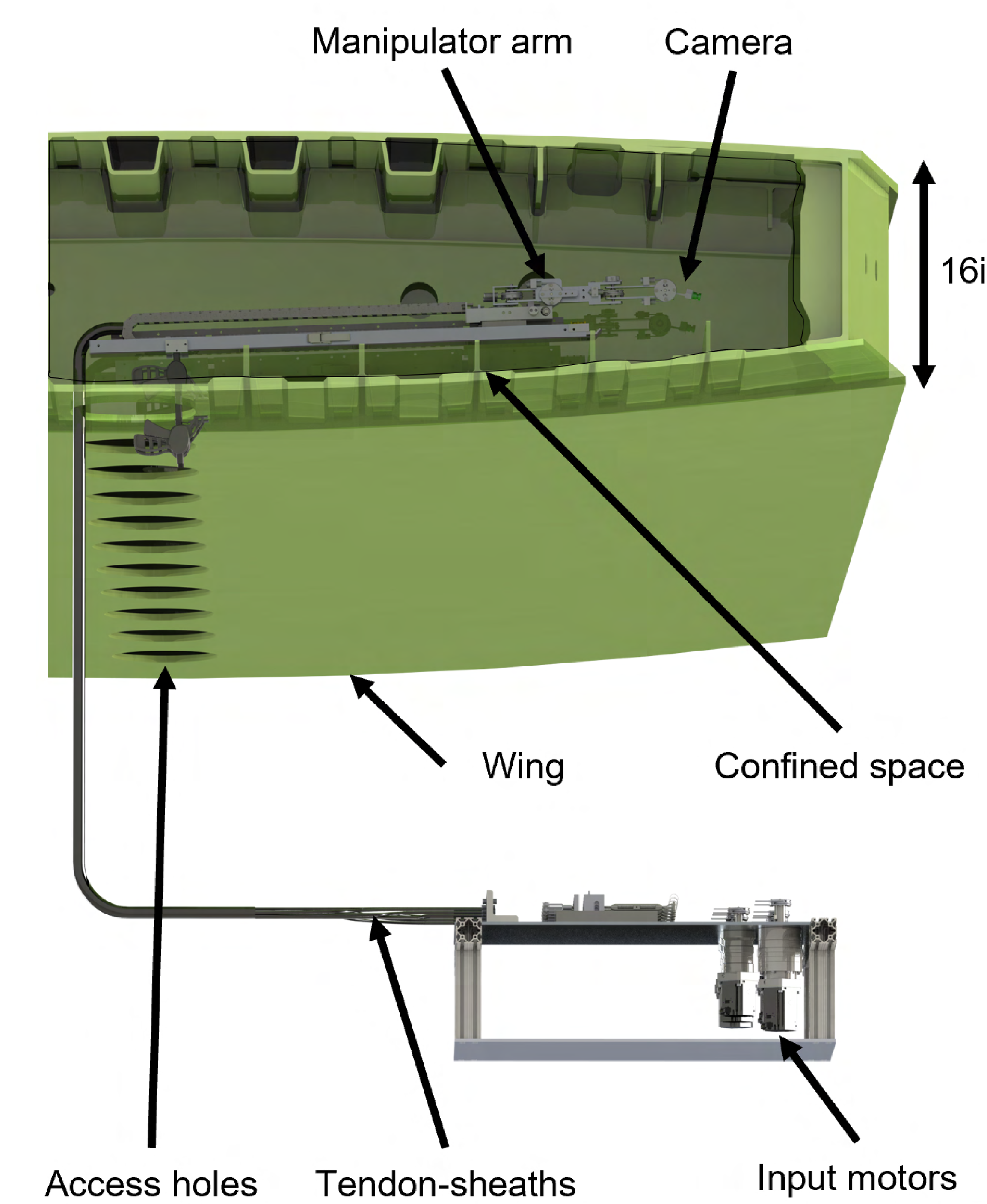
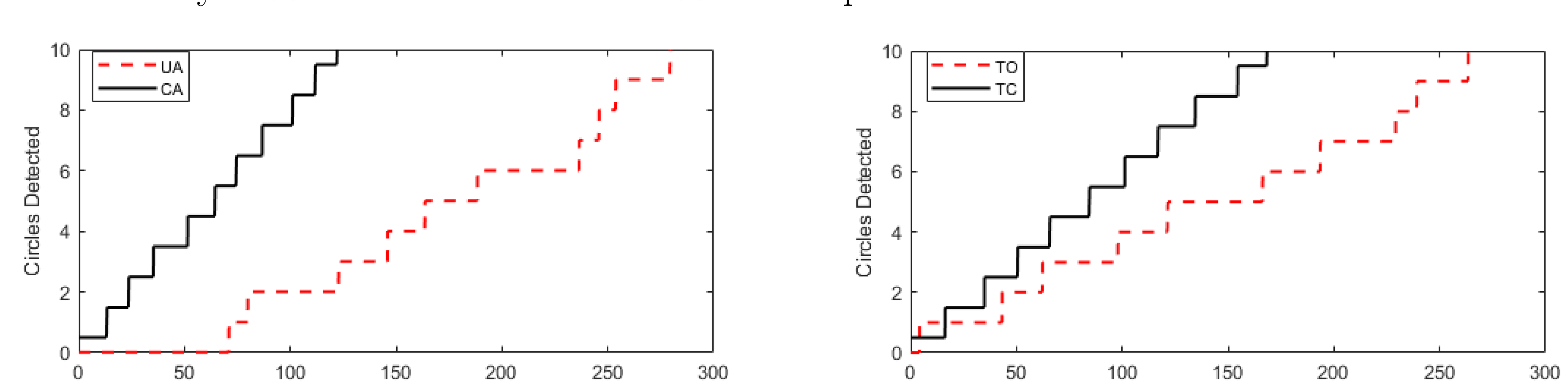


Figure: Tendon-sheath confined space robot actuated by motors placed outside of wing tank. Wing sectioned for clarity.

Results

Failures in uncompensated schemes increase the average time taken to reach a target. The failures are addressed using compensation, resulting in consistent average times to reach the goal. Compensation reduces completion time by 63% in automation and 37% in teleoperation.



(a) Automated methods (b) Teleoperated methods

Figure: Number of fasteners inspected over time for a) automation methods, b) teleoperation methods

Teleoperation Setup

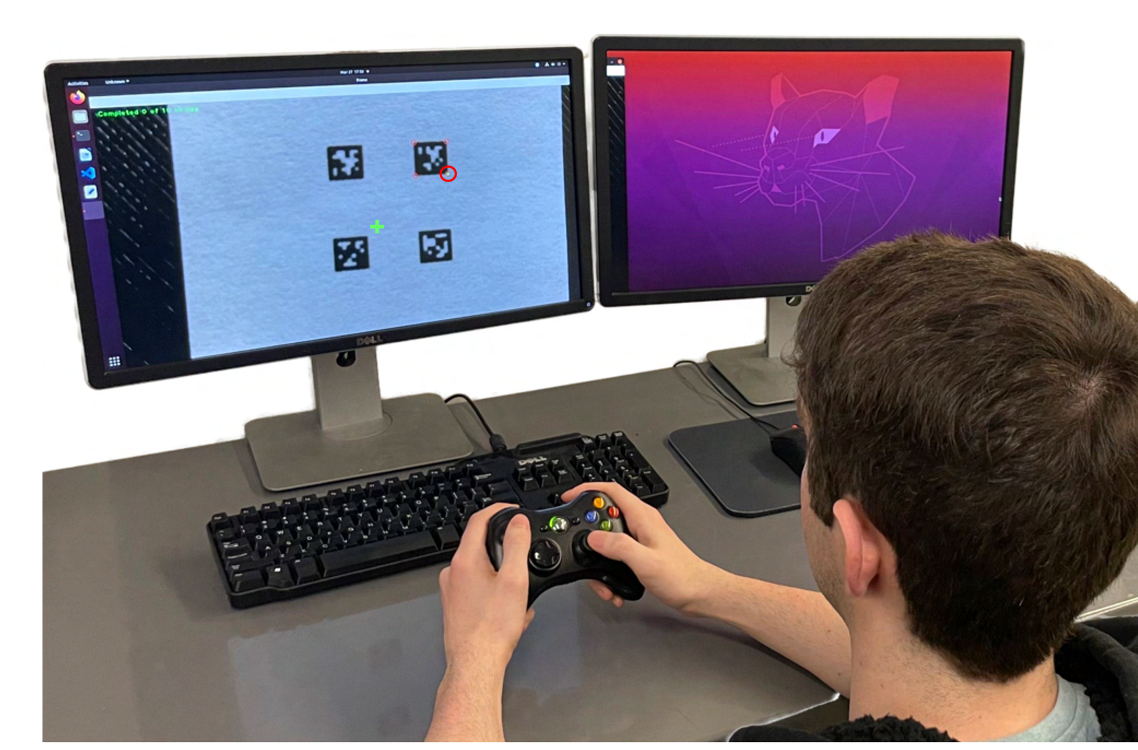


Figure: User teleoperation workstation