I&I ADAPTIVE FORCE-MOTION CONTROL FOR ARM MANIPULATION

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Introduction

We propose an adaptive force-motion controller for 2-DoF robot arm which is contrained to move in a line in $\mathbb{R}^2$ of unknown orientation. Our proposed design is based on adaptive immersion and invariance (I&I) control theory. In particular, we adapt to the unknown geometry of the motion constraint. The design is verified through numerical simulation and compared with a traditional hybrid force-motion controller.

Methods

Consider the 2-DoF arm with base fixed to the origin of the task frame $\mathcal{B}$ (Fig. 1). The end-effector of the arm stays in contact with a frictionless linear constraint.

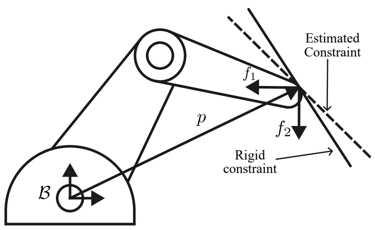

Figure 1: Constrained 2-DoF Arm Manipulator.

The task space dynamics with normalized mass, and the linear constraint are

$$\ddot{p} = u + f \tag{1}$$

$$\phi(p) = p_1 + Ap_2 + b = 0, \ A > 0 \tag{2}$$

where $p \in \mathbb{R}^2$ is the end-effector position, A is the constraint parameter, $f \in \mathbb{R}^2$ is the force due to the constraint, b is a constant, and u is the force that the robot exerts on the end-effector.The coordinate transformation $x = [\phi(p) \;\; p_2]^T$ decouples motion and force control of the end-effector, allowing us to independently track position and force trajectories x_{2d}, f_{1d}. We have

$$-A\ddot{x}_2 = u_1 + f_1 \tag{3a}$$

$$(A^2 + 1)\ddot{x}_2 = -Au_1 + u_2 \tag{3b}$$

With an auxiliary input $s = \ddot{x}_{2d} + k_v\dot{e}_2 + k_pe_2 + k_ie_{2i}$, where $e_2 = x_{2d} - x_2$, $e_{2i} = \int_0^t e_2 d\sigma$, $k_p, k_v, k_i > 0$ are constant, we define a traditional hybrid force-motion control (HMFC)

$$u = \left[-As - f_{1d} \quad s - Af_{1d}\right]^T \tag{4}$$

Substituting (4) into (3) leads to a stable closed-loop dynamics

$$A(\ddot{e}_2 + k_v\dot{e}_2 + k_pe_2 + k_ie_{2i}) = -e_{f1} \tag{5}$$

$$(A^2 + 1)(\ddot{e}_2 + k_v\dot{e}_2 + k_pe_2 + k_ie_{2i}) = 0 \tag{6}$$

When using an inaccurate parameter $\bar{A}$, an error in this parameter can lead to an unstable closed-loop:

$$A(\ddot{e}_2 + k_v\dot{e}_2 + k_pe_2 + k_ie_{2i}) = -e_{f1} - sz$$

$$(A^2 + 1)(\ddot{e}_2 + k_v\dot{e}_2 + k_pe_2 + k_ie_{2i}) = -(As - f_{1d})z$$

where $e_{f1} = f_{1d} - f_1$, z is the parameter error. With an function β to be determined and $\hat{A}$ to estimate, define

$$z = \bar{A} - A = \hat{A} - A + \beta(e_{2i}, e_2, \dot{e}_2) \tag{7}$$

In I&I theory, if we can stabilize z-subsystem about 0 by designing $\hat{A}$ and β, then the (z, x) system is rendered stable. Using this idea, a rigorous Lyapunov function design leads to the adaptive state feedback

$$\dot{\hat{A}} = -k_p\dot{x}_2^2 + s(s - \ddot{x}_{2d}) + f_{1d}e_{f1} \tag{8a}$$

$$\beta = \dot{e}_2\ddot{x}_{2d} + k_pe_2\dot{e}_2 + k_v/2\dot{e}_2^2 + k_ie_{2i}\dot{e}_2 \tag{8b}$$

$$u_1 = -(\hat{A} + \beta)s - f_{1d} \tag{8c}$$

$$u_2 = s - (\hat{A} + \beta)f_{1d} \tag{8d}$$

This leads to the closed-loop (1), (8) has a global exponential stable equilibrium $(x_2, \hat{A}) = (0, A)$, $\lim_{t\to\infty} e_{f1}(t) = 0$, and $\lim_{t\to\infty} e_2(t) = 0$.

Results and Discussion

Figure 2 shows a comparison between the traditional HMFC (4) and our approach under noisy force measurement. Both controllers are initialized with an incorrect value of A. Our approach achieves exponential convergence of e_2 and drives the force tracking error to a smaller neighborhood of 0 than the traditional HMFC.

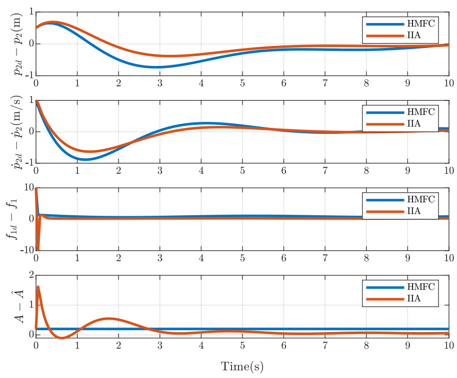

Figure 2: Setpoint tracking errors of ordinary and I&I adaptive force motion controller.

Conclusion

A novel I&I adaptive hybrid force-motion controller is developed and verified for arm manipulation. The method identifies the unknown linear constraint parameter under a noisy force measurement. Numerical simulation verified the controller stability and shows a better force tracking performance for our approach over its non-adaptive counterpart.

References

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