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Multi-source micro-friction identification for a class of cable-driven robots with passive backbone

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ABSTRACT

This paper analyses the dynamics of cable-driven robots with a passive backbone and develops techniques for their dynamic identification, which are tested on the H-Man, a planar cabled differential transmission robot for haptic interaction. The mechanism is optimized for human–robot interaction by accounting for the cost-benefit-ratio of the system, specifically by eliminating the necessity of an external force sensor to reduce the overall cost. As a consequence, this requires an effective dynamic model for accurate force feedback applications which include friction behavior in the system. We first consider the significance of friction in both the actuator and backbone spaces. Subsequently, we study the required complexity of the stiction model for the application. Different models representing different levels of complexity are investigated, ranging from the conventional approach of Coulomb to an advanced model which includes hysteresis. The results demonstrate each model's ability to capture the dynamic behavior of the system. In general, it is concluded that there is a trade-off between model accuracy and the model cost.

1. Introduction

Human–Robot Interaction has received increasing attention in the last three decades. New robots have been specifically designed to work in direct physical contact with humans. In contrast to industrial robots, which are designed to be stiff and accurate, robots designed to interact with humans often need to be *transparent* to the user. When physically interacting with humans, robots are used to assist/resist the human operator in specific maneuvers but are otherwise expected to offer minimal resistance to natural motions. For this purpose, these robots are designed to be intrinsically *lightweight* in terms of the inertia perceived by the human during interaction, e.g. at the handle. Ideally, the perceived inertia should also be *homogeneous* (the perceived inertia is the same across the whole workspace) and *isotropic* (the perceived inertia is the same along all possible directions of motion). H-Man [1], a planar robot, which exemplifies these properties, serves as the test platform for this study.

Most existing robotic manipulanda involve planar linkages based on serial or parallel mechanisms [2–6]. Cable-driven robots are intrinsically lightweight and also represent one possible solution to satisfy the need for a better cost-to-benefit ratio. In particular, this paper considers the class of *cable-driven robots with a passive backbone*, supporting an end-effector

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(or handle), which is driven remotely by cabled actuators. Two common sources of complexity in robots are backlash [7,8] on the joints and friction between the moveable parts. In this class of robot, however, the latter one is playing more significant role. The friction forces from the passive backbone and from the actuation system are reflected onto the handle through different kinematic maps (i.e. Jacobian matrices). This differs from the case of serial manipulators where friction arises only at the joint.

While equations are presented in the general case, we also show experimental results relative to a novel planar cable differential transmission robot, H-Man, which resulted from efforts to develop a practical, low-cost platform for human-robot interaction studies and robot-assisted neurorehabilitation. H-Man's mechanical simplicity allows for easy implementation of haptic channels, force fields, and a variety of impedance and position control paradigms, with a high degree of backdriveability and near perfect isotropy [9]. H-Man's hardware is low-cost relative to other functionally similar robotic systems which are commercially available; it is mechanically simple, and therefore easy to control, and intrinsically safe for humans. However, the cost of commercial load cells, which are typically necessary to accurately quantify haptic interaction, is a significant factor in the cost of the robot itself. Therefore, being able to accurately estimate haptic interaction through system characterization rather than direct measurement of force would significantly impact practicality of the device.

Additionally, it is possible to improve H-Man's backdriveability by compensating for the robot's dynamics. This is desirable in many situations such as implementing sensitive haptics or in neurorehabilitation applications where weak subjects may not be able to move a robot with a high degree of intrinsic resistance. In particular, friction typically plays a critical role in the resistance offered by the system during low acceleration movements carried out by humans. In order to accurately characterize the dynamics of the system, friction must be accurately identified. There exist a variety of techniques for parameter identification, ranging from the simplest model to the highly complex [10–13]. Unlike fine and precise robots, such as those for micro-positioning systems, applications for human-robot interaction might not require extremely precise dynamic models. It may be possible to balance the cost of external sensing hardware with model complexity to reduce system cost without sacrificing performance for a given application.

In this paper, we develop techniques for dynamic identification of friction in cable-driven robots with a passive backbone, and apply and test these techniques on H-Man. We investigate, in particular, the effectiveness of different types of friction models ranging from the Coulomb model to the advanced LuGre model. The objectives of this study are: (i) to analyze the phenomenon of multi-source friction, in particular static friction; and (ii) to investigate the effectiveness of friction models with varying degrees of complexity.

2. Dynamics of robots with cable actuation and passive backbone

When designing a cable-driven system for interacting with humans through a handle, the starting point is the definition of a desired configuration space for handle itself. Depending on the application, a user might be required to grasp a handle and move it in one degree of freedom (1 DOF, not necessarily linear), on a plane (2 DOF) or more degrees of freedom. Considering that a handle, as a rigid body in free space, has at most 6 DOF of motion, a passive mechanical support, or backbone, with M passive degrees of freedom can be designed to constrain unwanted motions along the remaining 6-M DOF. The advantage of such a class of robots, especially for haptic interaction, is that the passive backbone can be designed to be stiff, and thus reliably support the user's hand, and lightweight, while the cable-driven actuation can significantly reduce the inertia as the motors do not move with the manipulandum [14].

For this class of robots, system dynamics naturally occur in two different spaces, namely the *actuator space* and the *backbone space*, in contrast to others, e.g. serial manipulators. In the latter, the dynamics of serial linkages and the dynamics of motors act concurrently in the so-called joint space and their effects simply sum up, i.e. one could write equations for the serial linkages and simply add additional parameters to include inertia and friction due to motors. As we show next, this is not the case for cable-driven robots with passive mechanical supports. This is especially important when taking into account static friction, or stiction (pre-sliding form of friction) which plays a significant role in many robotic systems [12].

We assume that the desired motions of the handle are guided by an M DOF ($M \le 6$) passive mechanical support, or backbone. The handle and the backbone can, in this sense, be identified as their dynamics take place in an M-dimensional space backbone space. At the same time, we can consider N cables, where $N \ge M$, acting on the handles and transmitting forces produced by N motors, each with its own 1-dimensional dynamics. These motor dynamics can be combined in an N-dimensional space, called the actuator space.

2.1. Actuator space

The *actuator space* is given by coordinates $\{q_1,\ldots,q_n,\ldots,q_N\}$. In this space, the actuators produce force commands $\{u_1,\ldots,u_n,\ldots,u_N\}$, which account for cable tensions τ_n, friction $\tau_{rn}(\dot{q}_n)$ and inertia $I_n\ddot{q}_n$. The cable tensions produced by the actuators are thus characterized by the dynamics:

$$\tau = [\tau_1, \ldots \tau_n, \ldots, \tau_N]^T \text{ and}$$
$$\tau_n R_n = I_n\ddot{q}_n + \tau_r(q_n,\dot{q}_n) + u_n \tag{1}$$