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Available acceleration set for the study of motion capabilities for cable-driven robots

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ABSTRACT

The study of the ability of a cable driven robot (*CDR*) to generate motion between poses (*motion generation capability*) is important for many purposes such as motion planning and manipulator design. Existing analysis approaches that study CDR capability primarily do so by evaluating the mechanism's wrench generation abilities. Due to the nonlinear relationship between wrench and motion generation, these methods typically underestimate the true motion generation capability of a CDR and can result in conservative restrictions in operation. In this paper, two new metrics derived from the available acceleration set are proposed to better understand CDR motion generation capability. Using these metrics and the known properties of the static workspace, the maximum acceleration and speed capabilities of the CDR are quantified. This new information serves to better inform other technical aspects in the design, analysis and operation of CDRs, such as in workspace design and motion planning. To illustrate the application of the proposed metrics, two example robots are considered: a 2 link 2 DoF 4 cable CDR and a 6 DoF 7 cable CDR. The results show the insights into motion generation and how it provides new information to be used within motion planning and task scaling.

1. Introduction

Cable driven robots (CDRs) are a class of mechanism where cable actuators are used in place of rigid links. The advantages of CDRs include: increased reconfigurability, higher payload to weight ratio and potentially larger workspaces. With these benefits, CDRs have been studied for a range of applications including high-speed manufacturing [1], environment sensing [2], rehabilitation [3] and the analysis of musculoskeletal systems [4].

A unique feature in the study of CDRs is that the actuating cables can only operate under tension (*positive cable force*). This results in actuation redundancy and constraints on the system dynamics, creating challenges in the control and analysis of these mechanisms [5–7]. As a result, the analysis of system kinematics alone is not sufficient to determine if the manipulator has the capability to generate motion from one pose to another (*motion generation capability*). Understanding of this capability is important in the design [6, 8], trajectory planning [5,9,10,11] and construction of paths for CDRs. Typically, analyses of CDR capability consider the ability of the CDR to produce a set of desired wrenches [12–14]. This analysis has predominately been performed using two tools: workspace metrics and workspace conditions.

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Workspace metrics quantify a manipulator's capability by studying the set of wrenches that the CDR can generate (*available wrench set*). Examples of metrics include dexterity [15, 16], tension factor [17] and capacity margin [14, 18]. Dexterity and tension factor describe the distribution of cable forces in producing arbitrary wrenches. The *capacity margin* represents the shortest signed distance between the set of wrenches to be generated (*desired wrench set*) and the available wrench set, providing a measure of the CDR's robustness in producing the desired wrench set. Existing CDR metrics primarily focus on desirable manipulation qualities for the design of CDRs and therefore perform the analysis on the wrench set. However, wrench capability does not necessarily reflect the ability of the mechanism to produce motion. For motion generation purposes, an accurate measure of capability can be determined by direct analysis of the available set of joint velocities and accelerations. In serial robots, metrics such as dynamic manipulability [19] have been used to analyse the capability of the robot to produce acceleration, however, this class of metric does not take into account the unilateral actuation characteristics of CDRs.

While workspace metrics describe the wrench generation quality of the manipulator, *workspace conditions* define whether a set of wrenches or motions can be produced at a particular pose. Using these conditions, workspace analysis allows the capabilities of the manipulator to be studied by identifying the set of poses for which a workspace condition is satisfied. A range of different workspace conditions have been studied to consider different types of CDR capabilities, including the *static workspace* [5, 20], *dynamic workspace* [21], *wrench-feasible workspace* [13, 22] and *wrench-closure workspace* [17,23,24].

The wrench-closure workspace (*WCW*) is a commonly studied type of workspace that is defined as the set of poses in which any wrench can be produced when assuming that all cable forces are positive and unbounded [23]. While the WCW has not been typically used to analyse motion generation, the ability to produce any wrench means that the CDR is capable of producing all joint velocities and accelerations. This means that any trajectory that lies within a connected region of the WCW can be executed [25]. However, since motion generation only requires that there exists a single trajectory to connect two points, the generation of wrenches in all directions is not necessary. The WCW is therefore a conservative representation of the set of poses for which motions can be generated between, limiting its usefulness in the study of motion generation capabilities. Furthermore, the WCW may not be practical for motion generation of physical CDRs as the actual bounds of cable forces are not considered.

The wrench-feasible workspace (*WFW*) considers the set of all poses for which the desired wrench set can be produced using given upper and lower bounds on the cable forces [12]. The use of the WFW can result in less conservative estimates of the set of all poses for which a motion can be generated, by considering only the subset of directions required. However, since both the WCW and WFW specify the desired set in the wrench space, the choice of an appropriate wrench set for the purpose of motion generation is not clear due to the effect of the nonlinear mapping between kinematic and kinetics.

The dynamic workspace (*DW*) considers the set of all poses for which a desired set of accelerations and velocities can be produced using given upper and lower bounds on the cable forces [21]. Although this workspace directly considers accelerations, velocities and bounds on the cable forces, it is difficult to prescribe a desired set of accelerations and velocities in advance for analysing motion generation capability. A special case of the dynamic workspace is the static workspace (*SW*), where the desired accelerations and velocities are set to be zero [26], representing the set of all poses for which the CDR can sustain gravity. The SW has been suggested to have potential application in motion generation through task scaling [5, 27]. However, since this workspace only guarantees that the manipulator can remain in static equilibrium, the application of the SW to the study of motion generation has been limited. As such, if the capability of the CDR within the SW could be quantified, then the use of SW would be much more advantageous in the study of motion generation since it typically represents a much larger set of poses than other workspaces.

In this paper, two new workspace metrics are proposed for the analysis of motion generation capability within the SW. These metrics are obtained through the direct analysis of the acceleration space, where the available acceleration set is introduced as the set of accelerations that can be produced by the CDR for a given range of cable force bounds. From this set, the *acceleration capability metric* is defined as the minimum signed distance between the available and desired acceleration sets. This proposed metric provides an intuitive measure of the CDRs additional capability to generate motion at poses within the dynamic and static workspaces. It is also shown that poses within the static workspace with positive acceleration capability measure hold the property of local positive controllability. Using positive controllability theory [28–30] and the acceleration capability measure, the *maximum controllable speed* metric is then proposed as an estimate of the maximum speed at which the positive controllability property is maintained for poses within the SW. The insight into motion generation capability provided by these two new metrics is then shown through the consideration of two different case study CDRs, where the advantages of using the static workspace in combination with the capability measure for motion generation analysis are highlighted. These simulations are performed using CASPR: an open-source cable robotics analysis and simulation platform [31].

The primary motivation of this study is to increase the understanding of motion generation capability through the establishment of new metrics. Metrics derived in the acceleration space, represent direct metrics on the CDR's capability to alter its kinematics. These metrics can be made trajectory independent, such that they can provide new insight into a range applications including CDR design, task scaling and path planning. Most of the existing analysis of CDR capability has made use of wrench based techniques. These techniques can only be related to the system's kinematics through a nonlinear velocity dependent equation of motion, such that they are typically trajectory dependent and not proportional to acceleration capability. Metrics obtained through direct analysis of the acceleration space therefore offer additional insight, by more accurately quantifying the ability to produce motion which adds qualitative understanding of the CDR's true capability within the SW.

The remainder of the paper is organised as follows: Section 2 presents the background on wrench set analysis and the capacity margin. Section 3 introduces the available acceleration set and the acceleration capability measure. Using this measure, Section 4 presents sufficient conditions for the positive controllability of CDRs and then presents the maximum controllable