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A procedure to evaluate Extended Computed Torque Control configurations in the Stewart–Gough platform

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ABSTRACT

Parallel robots have become the best solution when high speed and/or accuracy are needed in industrial robotic operations. However, in order to meet the requirements of these tasks, advanced model based controllers such as the Extended CTC scheme are required. This CTC-based scheme requires the introduction of extra sensors in the passive joints of the parallel robot. This redundant information allows to increase the robustness and performance of the control law, leading to better trajectory tracking. However, in order to achieve the best performance, a proper extra sensor distribution is required. In this paper, a sensitivity analysis based approach is applied to the well known Gough Platform in order to evaluate different extra sensor distributions. The obtained results are compared with those obtained by a statistically significant set of simulations, demonstrating the effectiveness of the methodology.

1. Introduction

Due to their flexibility and reprogrammability, robots have became a key element in the automation of many industrial processes. Traditionally, industrial robots have been built following a serial topology in which the end effector is linked to the base by means of a single kinematic chain. This architecture maximizes the worskpace area and allows to perform a wide number of tasks.

However, in the need of increasing both productivity and quality, current industrial processes demand more and more high speed and accurate operations. Due to their high moving mass, traditional serial robots find it difficult to fulfill the requirements for these tasks. Thus, researchers have proposed alternative robotic architectures based on multiple kinematic chains that allow combining both high speed and accurate operation. These robotic architectures are known as parallel robots.

Parallel robots [1] are composed by a set of kinematic chains that join a mobile platform, in which the Tool-Center-Point (TCP) is located to a fixed one. This architecture, which allows a number of different variations, provides some advantages over the traditional serial robots. First, their structure provides them with a significantly higher stiffness. Second, the load/mass ratio is higher in parallel robots than in serial robots, as the load can be distributed among the different serial chains or limbs that join the mobile and fixed platforms. Third, the structure can be designed so that the actuators are located in the base of the robot, reducing the moving mass and inertia of the structure and allowing high speed operation. Finally, and due to the coupling between the different kinematic chains, errors in one can be compensated among the others, resulting in more accurate operations. Due to these advantages, parallel robots are considered the best solution when accurate, high speed or heavy load handling operations have to be performed.

However, being a more complex structure some disadvantages arise. Lack of closed form solution for the kinematic and dynamic model, reduced workspace, presence of inner singularities and nonactuated joints, collisions between the kinematic chains and orientation and position coupling are some of the issues derived from the structural complexity of these robots. These issues heavily limit their potential application in industry. Moreover, due to the fact that parallel robotics is a recently rediscovered research field, there are still many areas that have been not studied thoroughly yet. This way, in addition to the aforementioned issues, other challenges in areas such as control, dynamics or calibration arise.

This paper focuses in the control area of parallel robots. The main aim of the control law in parallel robotics is to maximize the dynamic performance of the robot while reducing the effect of the issues derived from the structural complexity of the robot. This way, a step towards the use of these robots in complex, robust and precise tasks in industry can be achieved.

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Yet, the main trend in this area has been to import directly the control approaches from serial robots to parallel robots without considering the specific features of the latter ones. This way, most of the position control related works in the literature fall into two categories: Local feedback control approaches and model based control approaches. The first is based on the use of a local PID based controller to control each joint independently from the rest of the mechanism. Simple Proportional-Integral-Derivative (PID) loop based schemes [2–4], joint dynamic model based approaches [5,6], Proportional-Derivative (PD) plus gravitation compensations schemes [7,8] or nonlinear PID based control laws [9,10] fall into this group. In general, these approaches are easy to implement due to their simple control law. However, as they do not consider the dynamic coupling between the joints, they do not provide good control performance when high speed and accuracy are required. Model based approaches, on the other hand, require the dynamic model of the parallel robot to define the control law and can provide very good performance when high speed, accelerations and accuracy are needed. One of the most extended approaches is the Computed Torque Control (CTC) scheme [11–13], which provides a good control performance if the dynamic model is accurate enough. However, obtaining an accurate dynamic model is a challenging task, as simplifications are usually made and some phenomena, such as friction or backlash, are not considered. Thus, in order to ensure the dynamic performance of the controller in presence of model parameter uncertainties, some authors have also proposed robust [14–16,6] or adaptive control [17,18] approaches.

From the analysis of the works proposed in the control area, it is clear that model-based schemes are the best approach when high-speed and accuracy requirements must be met in parallel robots. However, none of the previously analyzed strategies allows to exploit the full capabilities of parallel robots, as those approaches were originally designed for serial ones and do not consider the particularities of parallel robots. Among them, the appearance of nonactuated joints, the parallelism of the mechanical structure of the robot or the lack of calibration methodologies for parallel robots are remarkable. Hence, the performance of the aforementioned model-based schemes is limited in parallel robots due to these issues.

An interesting approach to increase control performance in parallel robots is the introduction of extra sensors in the nonactuated joints of the mechanism, so that the redundant data can be used to minimize the effect of parameter uncertainties and to implement a more efficient redundant control law in parallel robots. Although this approach increases the cost of the robot, the advantages of using redundant sensor data have been demonstrated by authors such as Merlet [19], Baron and Angeles [20], Marquet et al. [21], and Bauma et al. [22].

Based on this idea, in previous works of the authors, the Extended CTC approach was introduced [23,24]. This control approach is based on a modified CTC scheme that allows to introduce the redundant data provided by some extra sensors directly in the control law. This way, the Extended CTC combines the performance of the classical CTC with the robustness of sensor redundancy, providing better trajectory tracking than the classical nonredundant CTC approach. However, in order to achieve this performance, an appropriate redundant sensor distribution is needed, i.e. as the Extended CTC can be implemented with different extra sensor configurations, the one that provides the best performance should be selected to implement the controller.

Hence, in this paper a methodology to evaluate and compare different redundant sensor configurations for the implementation of the Extended CTC approach is introduced. The proposed methodology is based on the closed-loop sensitivity analysis of the different Extended CTC configurations and it allows to determine the best sensor configurations for a given parallel robot and nominal trajectory. In order to illustrate the approach, the methodology is applied to the Gough Platform, and the obtained results are validated with a set of simulations in which the control performance of the analyzed configurations are compared.

The rest of the paper is structured as follows. In Section 2, the Extended CTC approach is introduced. Section 3 describes the sensitivity analysis based methodology for evaluating different sensor configurations. In Section 4 the proposed methodology is applied to the Gough Platform and validated using a set of simulation results. Finally, the most important ideas are summarized.

2. Extended computed torque control approach

The classical CTC approach is based on the use of the Inverse Dynamic Model (IDM) to decouple and linearize the nonlinear dynamics of the robot. This way, if the IDM is accurate enough, the resulting system is a series of decoupled linear systems that can be easily controlled using a PD-based control law. This approach has been widely studied in the literature as it provides high dynamic performance in serial robots.

However, its application to parallel robots presents some issues that are not present in the serial robot case. First, the dynamic model of parallel robots is defined, in general, in terms of two sets of variables: The task coordinates $\mathbf{x}$, that define the location of the TCP of the robot in the fixed frame; and the set of joint variables $\mathbf{q}$, that includes both actuated $\mathbf{q_a}$ and nonactuated $\mathbf{q_{na}}$ joints. Second, the kinematic relations between these sets of variables are, in general, highly coupled, so a closed form relation cannot be calculated. And finally, as only data from active joints $\mathbf{q_a}$ is measured, the rest of the nonmeasurable variables $\mathbf{x}$ and $\mathbf{q_{na}}$ have to be estimated in order to calculate the IDM and implement the CTC control law. Thus, if model parameter uncertainties arise, the dynamic performance of the CTC controller is reduced.

The Extended CTC approach [23,24], is a generalization of the classical CTC approach that allows to define the control law in terms of an arbitrary set of variables called *control coordinates* $\mathbf{q_c}$. These coordinates group all measurable joint variables in the mechanism. Thus, if extra sensors are introduced in some nonactuated joints $\mathbf{q_{na}}$, the redundant data provided by these extra sensorized joints, grouped in vector $\mathbf{q_s}$, is combined with the always measurable active joints $\mathbf{q_a}$ in the control coordinates vector, so that $\mathbf{q_c} = \begin{bmatrix}\mathbf{q_a}^T & \mathbf{q_s}^T\end{bmatrix}^T$.

The use of redundant joint variable data in the control law provides several advantages over the classical CTC approach when applied to parallel robots. First, as some unactuated joints are sensorized $\mathbf{q_s}$, the number of unmeasurable variables decreases, allowing better control over the mechanism. Second, the redundant data grouped into the control coordinates $\mathbf{q_c}$ can be used to estimate the nonmeasurable variables: The task coordinates $\mathbf{x}$ and the strictly passive nonactuated joints $\mathbf{q_p}$, so that $\mathbf{q_{na}} = \begin{bmatrix}\mathbf{q_s}^T & \mathbf{q_p}^T\end{bmatrix}^T$. Thus, if model parameter errors arise, the estimation based on the redundant data will be more accurate than the nonredundant one. And finally, if an appropriate extra sensor distribution is selected, the Extended CTC control law provides better trajectory tracking than the classical nonredundant CTC approach even in the presence of uncertainties and nonmodelled physical phenomena, as demonstrated in [23,24].

Therefore, and being a generalization of the classical CTC approach, the Extended CTC can be implemented in both joint and task spaces. When implemented in the joint space, the control law is defined explicitly in terms of the control coordinates vector $\mathbf{q_c}$,

$$\begin{aligned}\boldsymbol{\tau} = {} & \hat{\mathbf{D}}(\hat{\mathbf{x}}, \mathbf{q_c}, \hat{\mathbf{q}}_\mathbf{p})(\ddot{\mathbf{q}}_{\mathbf{c_d}} + \mathbf{K_v}\dot{\mathbf{e}}_\mathbf{q} + \mathbf{K_p}\mathbf{e_q}) \\ & + \hat{\mathbf{C}}(\hat{\mathbf{x}}, \hat{\mathbf{q}}_\mathbf{p}, \mathbf{q_c}, \hat{\dot{\mathbf{x}}}, \hat{\dot{\mathbf{q}}}_\mathbf{p}, \dot{\mathbf{q}}_\mathbf{c})\dot{\mathbf{q}}_\mathbf{c} + \hat{\mathbf{G}}(\hat{\mathbf{x}}, \mathbf{q_c}, \hat{\mathbf{q}}_\mathbf{p}) \qquad (1)\end{aligned}$$