Mechanism and Machine Theory 106 (2016) 115–147

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmachtheory

# Minimal representation for the control of parallel robots via leg observation considering a hidden robot model

Sébastien Briot [a,*], Victor Rosenzveig [a], Philippe Martinet [a,b], Erol Özgür [c], Nicolas Bouton [c]

[a] Institut de Recherches en Communications et Cybernétique de Nantes (IRCCyN), UMR CNRS 6597, 1 rue de la Noë, 44321 Nantes, France
[b] École Centrale de Nantes, 1 rue de la Noë, 44321 Nantes, France
[c] Institut Pascal (UMR 6602) – Sigma Clermont – Campus des Cézeaux, 27 Rue Roche Genès, 63178 Aubière, France

ARTICLE INFO

*Article history:*
Received 24 January 2015
Received in revised form
30 August 2016
Accepted 31 August 2016

*Keywords:*
Parallel robots
Visual servoing
Controllability
Kinematics
Singularity

ABSTRACT

Previous works on the visual servoing of parallel robots using the observation of their leg directions validated the feasibility of the approach but they have enlighten two main surprising results for which no answer was given: (i) the observed robot which is composed of $n$ legs could be controlled in most cases using the observation of only $m$ leg directions ($m < n$), and that (ii) in some cases, the robot did not converge to the desired end-effector pose, even if the observed leg directions did (i.e. there was not a global diffeomorphism between the observation space and the robot space).

Recently, it was shown that the visual servoing of the leg directions of the Gough-Stewart platform and the Adept Quattro with 3 translational degrees of freedom was equivalent to controlling other virtual robots that have assembly modes and singular configurations different from those of the real ones. These hidden robot models are tangible visualizations of the mapping between the observation space and the real robots Cartesian space. Thanks to this concept, all the aforementioned points were answered for the mentioned robots.

In this paper, the concept of hidden robot model is generalized for any type of parallel robots controlled using visual servos based on the observation of the leg directions. It is shown that the concept of hidden robot model is a powerful tool that gives useful insights about the visual servoing of robots using leg direction observation. With the concept of hidden robot model, the singularity problem of the controller can be addressed and the convergence issues of the controller can be explained, understood and solved.

All these results are validated in simulations and through experiments on a Quattro robot.

## 1. Introduction

Parallel robots are mechanical architectures whose end-effector is linked to the fixed base by means of at least two kinematic chains [1]. Compared to serial robots, such robots are stiffer and can reach higher speeds and accelerations [2]. However, their control is troublesome because of the complex mechanical structure, highly coupled joint motions and many

---

[*] Corresponding author.

*E-mail addresses:* Sebastien.Briot@irccyn.ec-nantes.fr (S. Briot), Victor.Rosenzveig@irccyn.ec-nantes.fr (V. Rosenzveig), Philippe.Martinet@irccyn.ec-nantes.fr (P. Martinet), erol.ozgur@sigma-clermont.fr (E. Özgür), nicolas.bouton@sigma-clermont.fr (N. Bouton).

http://dx.doi.org/10.1016/j.mechmachtheory.2016.08.013

other factors (e.g. clearances, assembly errors, etc.) which degrade stability and accuracy.

Many research papers focus on the control of parallel mechanisms [2]. Cartesian control is naturally achieved through the use of the inverse differential kinematic model which transforms Cartesian velocities into joint velocities. It is noticeable that, in a general manner, the inverse differential kinematic model of parallel mechanisms does not only depend on the joint configuration (as for serial mechanisms) but also on the end-effector pose. Consequently, one needs to be able to estimate or measure the latter.

Past research works have proven that the robot end-effector pose can be effectively estimated by vision [3–5]. The most common approach consists of the direct observation of the end-effector pose [6–8]. However, some applications prevent the observation of the end-effector of a parallel mechanism by vision [9–12]. For instance, it is not wise to imagine observing the end-effector of a machine-tool while it is generally not a problem to observe its legs that are most often designed with slim and rectilinear rods [2].

A first step in this direction was made in [13] where vision was used to derive a visual servoing scheme based on the observation of a Gough-Stewart (GS) parallel robot [14]. In that method, the leg directions were chosen as visual primitives and control was derived based on their reconstruction from the image. By stacking the observation matrices corresponding to the observation of several legs, a control scheme was derived and it was then shown that such an approach allowed the control of the observed robot. After these preliminary works, the approach was extended to the control of the robot directly in the image space by the observation of the leg edges (from which the leg direction can be extracted), which has proven to exhibit better performances in terms of accuracy than the previous approach [15]. The approach was applied to several types of robots, such as the Adept Quattro and other robots of the same family [16,17].

The proposed control scheme was not usual in visual servoing techniques, in the sense that in the controller, both robot kinematics and observation models linking the Cartesian space to the leg direction space are involved. As a result, some surprising results were obtained:

1. the observed robot which is composed of $n$ legs could be controlled in most cases using the observation of only $m$ leg directions ($m < n$), knowing the fact that the minimal number of observed legs should be, for 3D unit vectors characterizing the leg directions, an integer greater than $n/2$
2. in some cases, the robot does not converge to the desired end-effector pose (even if the observed leg directions did)

without finding some concrete explanations to these points. Especially, the last point showed that it may be possible that a global diffeomorphism between the Cartesian space and the leg direction space does not exist, but no formal proof was given.

In parallel, some important questions were never answered, such as:

3. How can we be sure that the stacking of the observation matrices cannot lead to local minima (for which the error in the observation space is non zero while the robot platform cannot move [18]) in the Cartesian space?
4. Are we sure that there is no singularity in the mapping between the leg direction space and the Cartesian space?

All these points were never answered because of the *lack of existing tools* able to analyze the intrinsic properties of the controller. Additionally, we would like to point out that the understanding of the singularity cases of the mapping used in the controller is of the utmost because these singularities leads to the loss of controllability of the robot [19], and thus the define the boundaries of the reachable workspace for the controller. As a result, the accessible workspace for the robot controlled by leg observation is the intersection of two workspaces: (1) the singularity-free workspace of the robot and (2) the workspace free of singularities linked to the mapping between the leg direction space and the Cartesian space.

Recently, two of the authors of the present paper have demonstrated in [20] that these points could be explained by considering that the visual servoing of the leg directions of the GS platform was equivalent to controlling another robot "hidden" within the controller, the 3–$\underline{U}PS$[1] that has assembly modes and singular configurations different from those of the GS platform.

In both cases, considering this hidden robot model allowed the finding of a minimal representation for the leg-observation-based control of the studied robots that is linked to a virtual hidden robot which is a tangible visualization of the mapping between the observation space and the real robot Cartesian space. The hidden robot model:

1. can be used to explain why the observed robot which is composed of $n$ legs can be controlled using the observation of only $m$ leg directions ($m < n$),
2. can be used to prove that there does not always exist a global diffeomorphism between the Cartesian space and the leg direction space, but can also bring solutions for avoiding to converge to a non desired pose,
3. simplifies the singularity analysis of the mapping between the leg direction space and the Cartesian space by reducing the problem to the singularity analysis of a new robot,

---

[1] In the following of the paper, $R$, $P$, $U$, $S$, $\Pi$ will stand for passive revolute, prismatic, universal, spherical and planar parallelogram joint [21], respectively. If the letter is underlined, the joint is considered active.