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Force/position control of parallel robots using exteroceptive pose measurements

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Abstract The aim of this paper is to study the force and position tracking problem of parallel robot manipulators. Relying on a recent work showing that computed torque control in Cartesian space is suitable for parallel structures, we propose a parallel force position control scheme of a parallel robot based on the visual servoing of the end effector pose. Simulation results show the efficiency of the proposed approach.

Keywords Parallel robots · force control · parallel control · visual servoing

1 Introduction

Recently, parallel robots have drawn a lot of interest in the robotic community due to their theoretical superiority over the classical serial structures in terms of stiffness, accuracy, high speed and payload in spite of their more complex kinematics and smaller workspace compared to serial manipulators. However, the most attractive advantage of parallel robots is certainly their stiffness which is very interesting property for tasks involving strong interaction with the environment and requiring the control of contact forces in addition to accurate and fast motion. For such tasks, the interaction force must be controlled properly, since otherwise the arising contact forces may damage the object or the robot tip. To this end, different force control approaches have been proposed in the literature and applied for serial machines. The case of parallel machines has rarely been addressed in view of the complexity of their mechanical architecture, which leads to difficulty to obtain the relation determining the pose of the end effector from the joint coordinates (Forward Kinematic Model). The Forward Kinematic Model is indispensable to achieve robot position control in Cartesian space (using joint sensors) which is more convenient when the interaction forces between the robot end effector and the environment must be controlled as well. Also, force control

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involves the dynamics of the mechanical structure which is easily described in Cartesian space for a parallel machine. An alternative to obtain the end effector Cartesian pose without calculating the fastidious Forward Kinematic Model of a parallel robot is the use of an exteroceptive measure, specially, a camera since vision systems have shown good efficiency to guide robot using image information (visual servoing). The present work focuses on coupling force feedback and visual servoing to control both contact forces and the end effector Cartesian pose of a parallel robot. The two controlled variables (contact forces and Cartesian pose of the end effector) are directly measured by exteroceptive sensors (force sensor and camera) within parallel force/vision control architecture similar to that presented in [7]. The major advantage of the proposed control scheme is the opportunity of achieving both control goals directly in the task space without any use of the manipulator's forward kinematics. Also within this control architecture, the robot dynamic non linearities are fully compensated for, position and force are explicitly controlled and both sensors (force sensor and camera) control simultaneously all directions.
The remainder of the paper is the following: next section presents briefly previous work on force control, parallel machines and force/vision control, section III outlines the Cartesian general dynamics of the machine and the derivation of the adopted control law, section IV exposes the difficulties encountered in position/force control scheme of parallel robots and the proposed solution, in section V a description of the test-bed architecture is presented, the environment simulation and a discussion on the obtained results is to be found in section VI.

2 Preliminaries

2.1 Force control

Force control is essential for tasks involving interaction between the manipulator and the environment. Different control schemes have been proposed in the literature, as surveyed by DeSchutter and Spong [10]. The two basic approaches to force control are namely hybrid position/force control [27] and impedance control [13]. On one hand, hybrid control formalism partitions the six task space degrees of freedom into purely motion controlled and purely force controlled directions selected a priori upon an ideal description of the environment geometry. A diagonal selection matrix S dictates which degrees of freedom are force controlled and which ones are position controlled. Two independent controllers are then independently designed for each subspace and the orthogonality of the two subspaces is ensured within this control architecture. However, the geometric description of the environment is not always perfectly known and can change at every stage of the task execution. On the other hand, impedance control aims at developing a relationship between interaction forces and end effector position in contact with the environment without controlling force explicitly. The force exerted on the environment by the manipulator is dependent on its position and its impedance, and is indirectly controlled by prespecifying a robot positional reference trajectory which is determined regarding the dynamic properties of the environment. One of the major practical difficulties with this technique is that the environment dynamic properties (stiffness, damping and inertia) are usually not known precisely so that accurate reference trajectory can not be designed to achieve accurate contact force control. Other approaches were proposed to combine inherent advantages of both impedance and hybrid position/force control. External control [25] where the force control loop is closed around an internal position loop in a hierarchical way, and parallel (or implicit) control [7] which is able to control both position and force variables using two parallel force control and position control loops like the hybrid approach without any selection matrices. The conflict situations between the two control loop actions are managed by the dominance of the force control loop over the position control loop.

2.2 Parallel machines

Parallel structures offer superior rigidity relative to their size and weight, low mass and high acceleration with respect to existing serial machines. In the last years, they have been the subject of increasing attention and all the control schemes mentioned above which are essentially developed for serial robot manipulators, have been extended to parallel machines. Thus, hybrid control were applied to parallel mechanisms [18,29] , impedance control approaches were also used [2,11,4,5] as well as external control [28,12] and parallel control [6,14] . Nevertheless, the issue of force/position control of parallel robots remain rarely addressed in the robotic literature. This is due to the additional weaknesses like the limited work volume in comparison with that of serial manipulators, and the increased computational effort necessary to their control. Such problems were widely invoked and analyzed in the literature [9,19,15,21,31]. The major problem of parallel robots is the forward kinematics consisting in finding the possible pose of the platform for given joint coordinates which is more complex than its dual inverse kinematics for serial robots. Generally, numerical approaches (e.g. Newton-Raphson) are used to solve iteratively the set of non linear Forward kinematic equations starting by an initial estimate of the solution. This method leads sometimes to a solution which does not correspond to the current pose. The analytical approach is possible only for very restrictive particular structures of parallel robots, in the general case, the analytical approach leads to solve high degree polynomial equations. These drawbacks prevent these structures from being used in many high speed real-time engineering applications in spite of their potentially higher accuracy and rigidity.

2.3 Force/vision control

To cope with this difficulty, a very attractive alternative to model based control of the tool tip pose is to use an exteroceptive sensor (e.g. vision, laser). Indeed, it allows to directly measure the Cartesian pose of the parallel robot while traditional proprioceptive measure requires the calculation of the forward kinematic model. This idea was adopted in [23,1] using vision system for motion tracking purposes. To our knowledge, the use of cameras as position sensor in addition to the force sensor has never been suggested in the literature for the force control and motion tracking of parallel structures, whereas, it has been widely invoked in the case of serial manipulators. Indeed, the benefit of combining visual servoing and force feedback to increase the robot robustness and ability in manipulation tasks was recognized since 1973 when an insertion task was performed using visual feedback [30]. Hence, the issues concerning the integration of these two sensing modalities intrigued the robotic community: cameras are useful robotic sensors since they mimic the human sense of vision and allow the robots to locate and inspect the objects without contact. On the other hand, force sensors are useful to control the contact force in order to avoid damages in the robot end effector and manipulated object. This makes the combination of force and vision an attractive option for accurate control of contact tasks.
In [20], vision/impedance control was used for peg-in-hole insertion experiments where an

image-based visual servoing controller is closed around an impedance controller. The output of the 2D visual controller is integrated to generate the reference trajectory required by the impedance controller which is limited to pure damping. The same approach is adopted in [26] with a second order impedance controller. Theories of hybrid position/force control were adopted in [22] by substituting the position control loop by position-based visual servoing which permits fast approach of the end effector towards the surface to be contacted and gives information regarding the proximity of the workpiece. In [3], an appropriate hybrid (or shared) control for eye-in-hand vision and force integration was proposed, placed into a global 3D framework based on Mason's task frame formalism. In this work, a simulated 3D visual servoing loop is achieving motion control while a force control loop regulates contact forces via force feedback. This requires de derivative of the robot dynamic model.

3 General dynamics and control

Computed torque control is widespread for serial manipulators. For parallel robots, the Cartesian space computed torque control was shown more suitable [23] since the natural description of parallel machine dynamics is in the task space [9], in addition, the variables to be controlled are naturally defined in the task space. This nonlinear Cartesian dynamic decoupling approach was adopted in [6] within the parallel force/position control architecture introduced by Chiaverini [7] for a force/position controlled parallel robot as depicted in Figure 1.

Defining x as a set of independent Cartesian generalized coordinates, if the manipulator is interacting with the environment and exerting a force F in the task space, the equation of motion can be written as:

$$A_x(x)\ddot{x} + C_x(x,\dot{x}) + G_x(x) + F + D_{inv}(x)^t \Gamma_f = \Gamma_x \quad (1)$$

with:

$$x = FKM(q), q = IKM(x) \quad (2)$$

$$\dot{x} = D_{inv}(x)^{-1}\dot{q}, \dot{q} = D_{inv}(x) \cdot$$

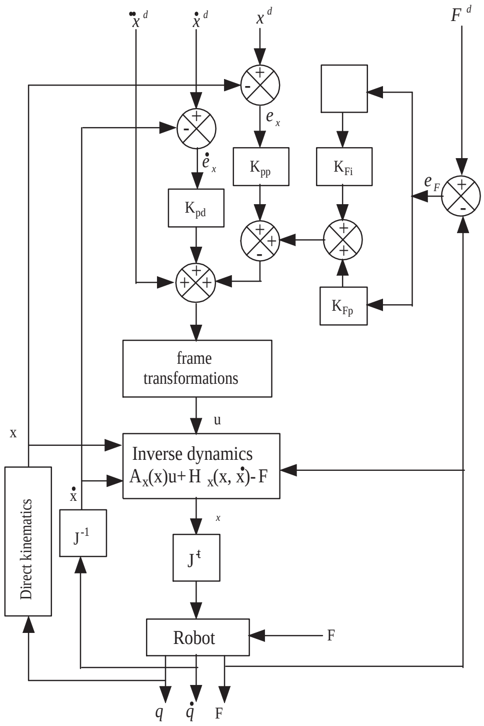


Fig. 1 The parallel force position control scheme adopted in [6]

linear feedback is hence possible . Assuming that position and force control loops are respectively a PD and PI control laws (see Figure 1):

$$u_p = \ddot{x}^d + K_v(\dot{x}^d - \dot{x}) + K_p(x^d - x) \tag{7}$$

$$u_f = K_f(F^d - F) + K_i \int_0^t (F^d - F) d\tau \tag{8}$$

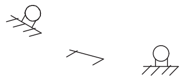
with:

$$u = u_p + u_f \tag{9}$$

where x^d, $\dot{x}^d$ and F^d are respectively the desired values of the Cartesian position, its derivative and the contact forces. The resultant control law applied to the actuators can hence be written as:

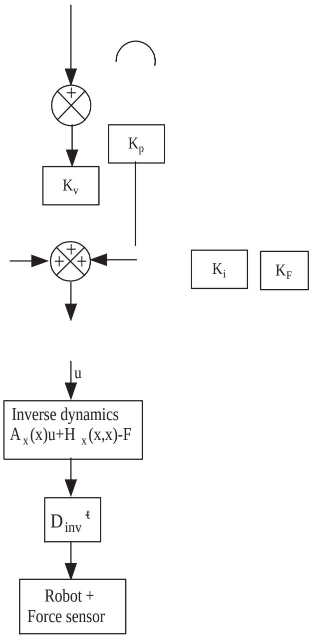
$$\begin{aligned} \Gamma_x = \hat{A}_x(x)[\ddot{x}^d + K_v(\dot{x}^d - x) + K_p(x^d - x) + K_f(F^d - F) \\ + K_i \int_0^t (F^d - F) d\tau] + \hat{C}_x(x, \dot{x}) + \hat{G}_x(x) + \hat{F} + D^t_{inv}(x)\hat{\Gamma}_f \end{aligned} \tag{10}$$

This choice allows for explicit servoing of both position and force variables along all directions of the task space with dominance of force control loop over the position one thanks to the integral action.



- Wire based systems: A number of wires are connected to the robot end effector to constitute triangles and the pose is estimated by mean of triangles geometry. This technique has low cost but is not completely safe since wires can constitute a physical limitation (interference among wires and wrapping risks).
- Mechanical device: One could also add a serial mechanism in parallel with the parallel robot and calculate its pose (e.g. Faro or Romer arms), which is the same as the parallel robot's one, by means of the well known Forward Kinematics of serial structures. This method is limitative since the added serial robot must be sufficiently light to limit the influence on the parallel robot dynamics and thus it may be subject to flexion leading to non accurate pose estimation.
- Laser interferometer: This device can precisely guide the robot at high sampling rate if appropriately calibrated but it is expensive and very restrictive regarding its sensitivity to environmental effects (namely, the laser beam must not be interrupted). Also when possible, the orientation measurement is not very accurate.
- Vision system: A vision system needs calibration but it is suitable for a large class of structures, low cost, easy to use and rather accurate since it allows easily to obtain redundant information on the end effector pose.

In view of the growing efficiency of image processing algorithms and image acquisition technology, vision constitutes an adequate sensor that we propose to employ for end effector pose measurement. In this way, the force/position control scheme proposed in [6] (Figure 1) can be reduced to the one depicted in Figure 3 where no calculation of the Forward Kinematic Model is required. In this control scheme, both force and position variables are controlled in the task t .08125507-0.0799658(,)-277182(33)-0.184437(y)-277.865(m)0.145744(e)-0.0812556(a)-0.079125517(c)15.1135(



+
K_p
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u
Inverse dynamics
$A_x(x)u+H_x(x,x)-F$
D_{inv}
Robot +
Force sensor

presented as [16]:

$$\Gamma = Dinv(x)^{-t}[F_p + \sum_{j=1}^{4} J_{pi}^t J_i^t H_i] + \Gamma_f \tag{11}$$

where F_p is the dynamics of the mobile platform, J_{pi} a Jacobian matrix linking the Cartesian coordinates of the end of the leg i to the Cartesian coordinates of the end effector, J_i the Jacobian matrix of the leg i (serial structure) and H_i is the inverse dynamic model of the leg i. Many well known methods can be used to calculate H_i. Newton-Euler formalism is used to derive the dynamics of the mobile platform. Assuming that the end effector is exerting a force F on the environment, the dynamics of the mobile platform is given in the case general of six DOF by the following Newton-Euler equation:

$$F_p = A_p\ddot{x} + \begin{bmatrix} \Omega \times (\Omega \times MS_p) \\ \Omega \times (I_p \Omega) \end{bmatrix} - \begin{bmatrix} m_p I_3 \\ M\tilde{S}_p \end{bmatrix} g + F \tag{12}$$

where:

- A_p: is the 6

	X (m)	Y (m)	Z (m)	$\theta(rad)$
X_0	0.676	1.049	0.771	0.112
X_c	0.776	0.949	0.971	-0.063
ΔX	0.1	-0.1	0.2	-0.175

Table 1 Desired trajectory

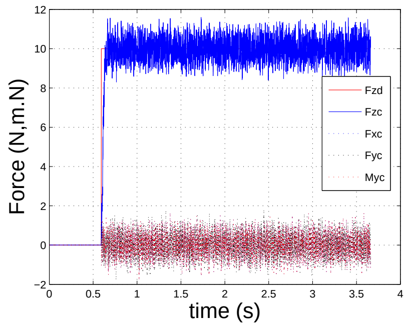
Case1, Figure 5: A low cost vision system with a roughly calibrated camera is used and precision of 0.2mm on translations and 0.02^0 on rotation is considered. The force sensor's resolution is equal to $[\frac{1}{160}N, \frac{1}{160}N, \frac{1}{80}N, \frac{1}{32000}N.m, \frac{1}{32000}N.m, \frac{1}{32000}N.m]$ (Gamma sensor of ATI).

Case2, Figure 6 : A highly sophisticated system vision with precisely calibrated camera is used and a precision of 0.05mm on translations and 0.005^0 on rotation is considered. These precision is realistic and available actually [8]. The same force sensor is kept.

Case3, Figure 7 : A futuristic case is considered and a precision of 0.01mm on translations and 0.001^0 on rotation is taken. This precision is available now only in static case. The same force sensor is kept.

Case 4, Figure 8 : A fourth and last case is considered in which the accuracy of the force sensor is ten times less than that used in the previous three cases with the system vision used in Case 2.

In all cases, the following subfigures are given: subfigure (a) displays both the desired and actual contact forces/moments; subfigure (b) displays the difference between the desired and actual contact forces/moments; subfigure (c) shows both the desired and actual 3D trajectories of the tool; and subfigure (d) displays the difference between the desired and actual tool position coordinates along the trajectory. Assume that the tool axis is rigidly fixed at the center of the mobile platform and that the contact surface is parallel with the x-y plane. The stiffness value coefficient of the contact surface is set as $k_e = 10^4 N.m^{-1}$ and the contact model is expressed in a scalar form as: $F = k_e(x^d - x)$. The tool, which is initially not in contact with the surface (this one is fixed at 0.971m from the base along Z axis) at the position $x_0 = [0.676, 1.047; 0.771; 0.112]^t$ expressed in the base frame, has to exert a constant force of 10N perpendicularly to the contact surface (along the z-axis direction) while following twice a circular trajectory of 0.05m diameter around $x_c = x_0 + [0.1, -0.1, 0.2, -0.175]^t$ as resumed in table 1. In all cases, the constant gains of the controller in (10) are fixed at: $k_p = 3(2\pi\omega)^2$, $k_v = 3(2\pi\omega), k_f = 0.05\omega$ and $k_i = 5\omega$ where ω is tuned at 10 rad/s under 1KHz sampling rate.


Force (N,m.N)
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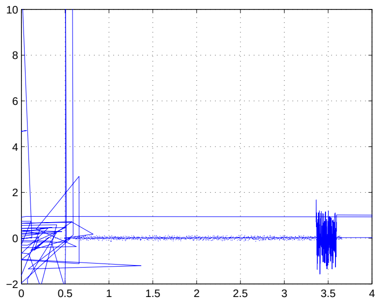

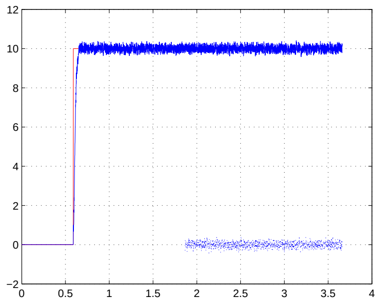
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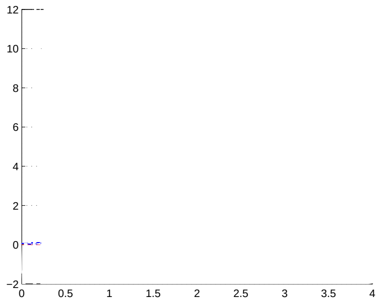
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