Some Issues on Dynamic Control of Parallel Kinematic Machines

Flavien Paccot[1] Omar Ait-Aider[1] Nicolas Andreff[1,2] Philippe Martinet[1,3]

***Abstract*— In this paper, a discussion on parallel kinematic machine dynamic control shows that such a control has to be thought over again. Hence, the well-known computed torque control approach is revisited and is shown, when it is performed in the Cartesian space and including a Cartesian space dynamic model, to be definitely relevant for parallel kinematic machines. Moreover, it is shown that greater improvements can be expected with an exteroceptive measure of the end-effector pose. Finally, experimental results on a complex prototype give a comparison between a linear single-axis control and a computed torque control to prove our assertions.**

I. Introduction

Parallel kinematic machines are spreading in the industry because of their advantages over serial kinematic machines, such as stiffness, high load and high speed capacities [1]. Nevertheless, these good dynamic performances are not always achieved [2]. Indeed, improvements are still needed in design, modeling, identification and control to take advantage of parallel kinematic machine performances [3]. In our mind, the development of adapted control strategies is probably the field where remains the largest potential for improving the tracking performances at high speed.

As far as we know, industrial parallel kinematic machines have in most cases a linear single-axis control. This control strategy seems to be efficient with regards to its large presence in machining. However, the dynamic behaviour of a parallel kinematic machine is strongly nonlinear due to a dynamic coupling between the kinematic chains linking the end-effector to the fixed basis, also known as legs. Therefore, a linear control strategy ensures a good accuracy only at low speed and in a small part of the workspace [4]. Moreover, the efficiency is not homogeneous over the workspace since the dynamic behaviour depends on the end-effector pose [5]. To take into account this heterogeneity, a restricted workspace can be defined as a space where stiffness, kinematic and dynamic properties allow for a good accuracy [1], [6]. In addition, an optimal path can be computed with regards to the dynamic behaviour [7]. Therefore, these solutions deal with the weakness of the linear single-axis control by proposing a path with restricted speed in a restricted working space, leading to a suboptimal use of parallel kinematics machine.

However, improving the dynamic performance of a machine by employing a nonlinear dynamic control, such as the so-called computed torque control, is a well-known solution [8]–[10]. These control strategies, including the inverse dynamic model of the machine, are widespread for industrial serial manipulators. However, the latter has never been employed for industrial parallel kinematic machines whereas a great improvement in dynamic accuracy and workspace use could be expected. Indeed, the transposition from serial robotics to parallel one is not always straight forward. The small amount of experimental results in the literature proves the troubles in setting up a dynamic control for a parallel kinematic machine and obtaining good performances [9], [10].

Actually, the modeling errors are the main limitation in the accuracy and stability of a computed torque control [8]. However, the dynamic modeling of parallel kinematic machines is quite complex [11]. Therefore, the amount of computation often imposes simplifications [10], [12]. This leads to non neglectable modeling errors with regards to accuracy and stability. These errors can be decreased with a kinematic and dynamic identification. The kinematic identification essentially reduces the influence of assembly errors [13] while the dynamic identification reduces the influence of frictions and internal torques due to assembly errors [14]. In many cases, the identification is nevertheless not sufficient for performing a stable and accurate computed torque control. In these cases, robust techniques are generally employed to cope with the error influence [10]. Therefore, an industrial implementation of such control strategy is not relevant since the understanding and the mastery of robust techniques require heavy skills and means.

However, in many cases, the inverse dynamic model of a parallel kinematic machine is written in the joint space as a function of the joint variables, like a serial kinematic machine [11]. Nevertheless, since the kinematics are defined by the end-effector configuration, the dynamics should also be computed in the Cartesian space (SE_3), written as a function of the end-effector pose and its time derivatives and mapped into the active joints space [9], [15]. In this case, the dynamic modeling requires less computation and thus presents less modeling errors than a joint space modeling. Nevertheless, the use of a Cartesian space dynamic model is only relevant with a Cartesian space control as developed in further words.

The motivation of this paper is to develop this discussion on the dynamic control of parallel kinematic machines. It is thus originally shown that a Cartesian space control is the most relevant solution to ensure correct tracking. Experimental results are proposed to emphasize this discussion. Notice that the reader is expected to be familiar with kinematic and dynamic modeling as well as with standard control schemes. Thus, we can focus only on the analysis of the existing

[1]LASMEA - UMR CNRS 6602, Université Blaise Pascal Clermont Ferrand II, Aubière, France

[2]LAMI, Insitut Français de Mécanique Avancée (IFMA), Aubière, France

[3]ISRC, Sungkyunkwan University, Suwon, South Korea

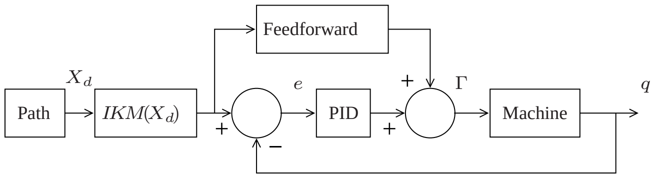


Fig. 1. *Single-axis control with PID controller and feedforward*

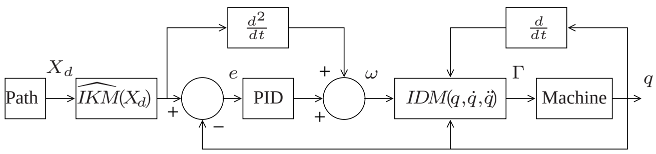


Fig. 2. *Joint space Computed Torque Control for serial kinematic machines*

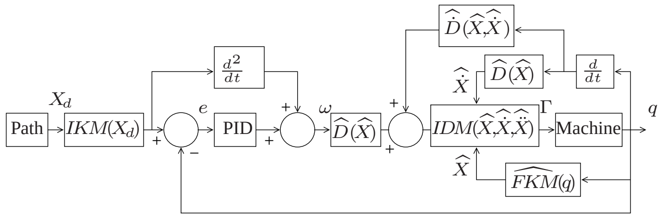


Fig. 3. *Joint space Computed Torque Control for parallel kinematic machines, explicit form*

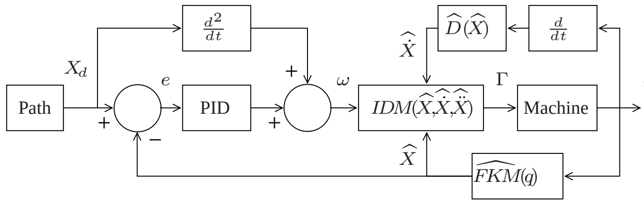


Fig. 4. *Cartesian space Computed Torque Control for parallel kinematic machines*

schemes. The core of this paper is organized as follows: Section II is devoted to control, Section III presents the test-bed, namely the Isoglide-4 T3R1 [16], and its dynamic modeling and Section IV contains experimental results.

II. Dynamic control of a parallel machine

As stated above, industrial parallel kinematic machines use in most cases a linear single-axis control with a linear feedforward in terms of speed and acceleration (see Figure 1, where IKM is the Inverse Kinematic Model). However, to ensure a good accuracy, the workspace and speeds should be restricted [1], [6], [7].

Indeed, the strongly nonlinear dynamics of a parallel kinematic machine have to be compensated for to increase attainable workspace, speed and accuracy. The so-called computed torque control is a well-know solution for serial manipulators [8]. It encloses an inverse dynamic model (IDM) depending on joint positions, speeds and accelerations (see Figure 2). Notice that $\widehat{IKM}$ is a numerical solution to the inverse kinematic problem, obtained by a numerical inversion of the closed-form forward kinematic model and often performed off-line. This control ensures excellent tracking performances. However, its transposition to parallel kinematic machines is harder than for the linear single-axis controller. Let us see why.

Computed torque control of a parallel kinematic machine met in the literature is generally performed in the joint space [10]. Nevertheless, in most cases, the inverse dynamic model of a parallel kinematics machine depends only on the end-effector pose, velocity and acceleration [9], [15]. Therefore, performing a computed torque control in the joint space requires transformations from joint space to Cartesian space. These forward transformations have a closed-form expression for most serial kinematic machines. However, the duality between serial and parallel kinematic machine implies that most parallel kinematic machines have algebraic inverse kinematic models and numerical forward kinematic models [17].

Consequently, the presence of on-line computation increases the complexity of the control scheme. We propose an explicit form of this control to emphasize the inherent complexity of joint space computed torque control (see Figure 3 where $\widehat{FKM}$ is a numerical solution to the forward kinematic problem and $\widehat{D}$ is the computed forward instantaneous kinematic matrix). Thus, heavy on-line computation decreases control speed, accuracy and stability. Consequently, a joint space computed torque control for a parallel kinematic machine is rarely met alone but with a robust controller [10].

On the opposite, using a Cartesian space dynamic model implies using a Cartesian space computed torque control, as mentioned by Callegari [9]. We propose here a deepest analysis of this assertion. The Cartesian space computed torque control is well-known for serial kinematic machines [8]. However, it requires, in this case, more computation than a joint space computed torque control, since the numerical inverse instantaneous kinematic matrix is used on-line. It may lead to a decrease of control speed, accuracy and stability. Consequently, the Cartesian space computed torque control of serial kinematic machine is rarely used. On the opposite, by comparing Figure 3 and Figure 4, which represents the Cartesian computed torque control for parallel kinematic machines, it can be noticed that less numerical transformations are used. Therefore, a more stable and accurate control is performed [18]. Hence, only from the control scheme analysis, a Cartesian space computed torque control is relevant for parallel kinematic machines. Nevertheless, we can point out some additional practical advantages.

Firstly, trajectories are most often planned in the Cartesian space. Thus, a Cartesian space control is more natural since the control is performed directly in the task space. In addition, the desired trajectory is not transformed with the inverse kinematic model, which can present errors. Consequently, the reference trajectory is not biased by the modeling or identification errors. Furthermore, the Cartesian space is the state space of most parallel kinematic machine since the latter are completely defined by their end-effector pose [19].

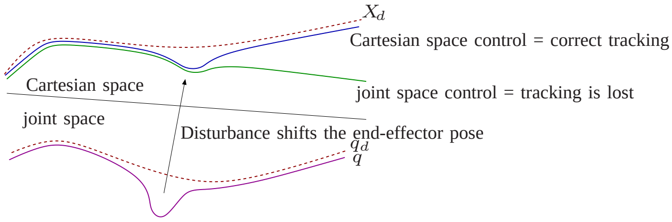


Fig. 5. *Cartesian space ensures correct end-effector reference tracking contrary to joint space control*

Therefore, a Cartesian space control is a state feedback control, which is known to ensure a better accuracy and robustness than a control without a state feedback.

Secondly, a better end-effector trajectory tracking is ensured with a Cartesian space control than a joint space one. Indeed, one joint variable configuration leads to several end-effector poses [20]. In the worst cases, a disturbance on joint trajectory can thus shift the end-effector position without changing joint configuration. This can happen especially in the neighborhood of singularities (assembling mode changing trajectory [21]) or cups points (non-singular posture changing trajectory [22]). This change of the end-effector pose is not observed by a joint space control whereas a Cartesian space one is able to do so (see Figure 5). Consequently, the Cartesian space control tries to bring back the end-effector pose to its reference or fails when the singularity can not be crossed again. On the contrary, a converging joint space control can not tell whether the Cartesian reference tracking fails or not.

Last but not least, even on planned path dealing with kinematic and dynamic constraints, the joint position errors are independent from each other when using a joint space control. Therefore, the constraint can not be ensured and two types of defects may appear: uncontrolled parasite end-effector moves or internal torques on the contrary if these moves are impossible, thus degrading passive joints. Like two-arm robot control, Cartesian space control can minimize, or cancel in the best cases, internal torques [23]. Indeed, the regulated errors, which are end-effector pose errors, are naturally compatible with the end-effector moves.

Consequently, Cartesian space control is particularly relevant for parallel kinematic machines. Nevertheless, the presence of the forward kinematics in the feedback loop can reduce the improvement of a Cartesian space control over a joint space one. In the general case, this numerical transformation can disturb the feedback loop thus leading to stability, accuracy and speed losses and thus imposing a robust control [12]. In the author opinion, this issue could be improved by using performant forward kinematics resolution methods [24] or metrological redundancy which simplifies the forward kinematics [25]. Of course, the ability of employing these methods at high rate should be tested. Anyhow, the forward kinematics of some parallel kinematic machines have a closed-form expression, like in the Isoglide-4 T3R1 case [16]. Thus, the estimation of the end-effector pose is reliable and stable and a Cartesian space control could be used.

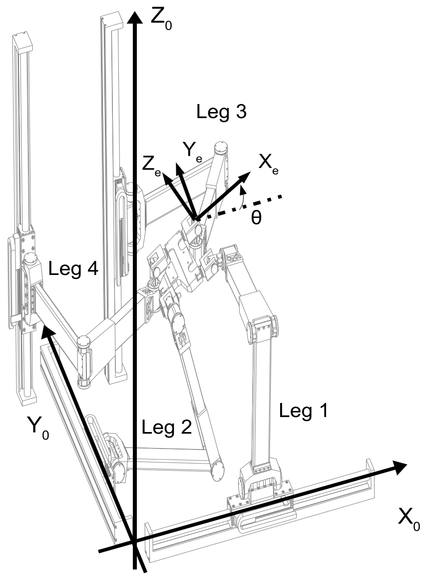


Fig. 6. *Global view of the Isoglide-4 T3R1*

However, a kinematic model is always biased by the unavoidable geometrical and assembly errors contrary to a direct measure using simpler physics, such as optics. As far as we know, the means to measure an object pose (Cartesian position and orientation) are rare. For example, a laser tracker is an accurate sensor (about $20\mu m$ for recent sensors) but not fast enough ($20m.s^{-2}$ maximal object acceleration) [26], [27]. To our knowledge, this sensor has not been integrated in a control scheme but it is only used for calibration [27]. On the opposite, the computer vision is a well known solution for robot control [28]. However, the accuracy and speed are generally quite low. Nevertheless, the technological advances allows for a fast and accurate vision-based control in a near future [29], [30].

III. Application on the Isoglide-4 T3R1

A. Presentation of the test-bed

To validate the above discussion, we propose to apply the Cartesian space dynamic modeling and computed torque control to the Isoglide-4 T3R1. This parallel kinematic machine is a fully-isotropic one with decoupled motion (see Figure 6 and [16]). It is a four degrees of freedom machine with three translations and one rotation. This machine is designed for high speed machining. Hence, stiffness requirements impose an important weight: $31kg$ per leg and $14kg$ for the end-effector.

The main advantage of the Isoglide-4 T3R1, as far as control is concerned, is to have a closed-form expression of the forward kinematic and instantaneous kinematic models:

$$\begin{cases} X_e &= q_1 - X_0 \\ Y_e &= q_2 - Y_0 \\ Z_e &= q_3 - Z_0 \\ sin\theta &= \frac{q_4 - q_3 + \delta Z}{L} \end{cases} \quad (1)$$

and

$$D(X) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -\frac{1}{Lcos\theta} & \frac{1}{Lcos\theta} \end{pmatrix} \quad (2)$$

where $X = [X_e \ Y_e \ Z_e \ \theta]^T$ is the end-effector pose, X_0, Y_0, Z_0 and δZ are constant parameters depending on the actuators position in the reference frame and L is one dimension of the end-effector.

Khalil's method [31] is preferred over the classical Cartesian space dynamic modeling [9], [15] since this approach is easy to implement and ensures the known advantages of a Newton-Euler method in a control context. In the Isoglide-4 T3R1 case, Khalil's method leads to a closed-form inverse dynamic model depending only on the end-effector pose and time derivatives. For conciseness concern, the expression of the obtained model is not given here.

This test-bed is well suited to the validation of the approach, since its weight prevents us from neglecting the dynamics. Moreover, its straightforward kinematic models allow for using a Cartesian control easily and compensate for the technological lack of reliable and accurate high-speed sensor of the end-effector pose.

IV. Experimental results

A. Dynamic identification

In order to fit the inverse dynamic model to the real dynamics of the machine and ensure the best performances for computed torque control, dynamic identification was realized (see Table I). The method and notations used here were proposed by Guégan [32]. Results lead to an observation matrix condition number of 355.56 which is relatively good. Inertia parameters (MXR_3, ZZR_3, ZZR_2, M_t, M_{R1}) are identified with a standard deviation from 0.40% to 1.29%, friction terms (Fs_i and Fv_i) from 1.07% to 6.34%. Let us remark that some parameters describing the end-effector can not be identified because the end-effector is lighter than the legs, thus having a little influence on dynamics. Anyhow, the good results of the identification process allows for ensuring a stable and accurate computed torque control.

B. Dynamic control

The Isoglide-4 T3R1 is designed to be controlled either in joint space or in Cartesian space thanks to the kinematic decoupling. Consequently, we first propose a comparison between linear single-axis control and computed torque control in *joint space*.

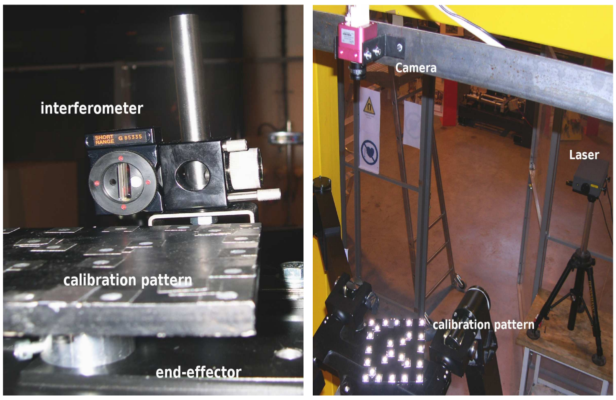
To achieve this comparison, the end-effector trajectory is measured with a 512×512 camera as exteroceptive measure running at $250Hz$. This provides us with a measure of the real end-effector trajectory instead of a model biased estimation. A comparison between the camera and a laser interferometer is performed (see Figure 8) showing that the camera has an average accuracy of $26\mu m$ and validating further results.

Both control schemes have the same gain tuning with same cut-off frequency (ω_c) of $5Hz$. Nevertheless, derivative gain

Parameter	CAD values	Identified values	Units	σ(%)
MXR_3	3.235	5.054	$kg.m$	0.42
ZZR_3	1.787	2.443	$kg.m^2$	1.29
ZZR_2	6.429	8.420	$kg.m^2$	0.54
M_t	45.011	39.513	kg	0.62
M_{R1}	31.4380	39.999	kg	0.40
M_PX_P	2.059	0	$kg.m$	
YY_P	0.411	0	$kg.m$	
$Mcomp_3$	45.011	49.180	kg	0.50
$Mcomp_4$	31.4380	41.005	kg	0.39
Fs_1		10.907	N	2.76
Fs_2		25.558	N	1.25
Fs_3		21.044	N	1.71
Fs_4		28.980	N	1.07
Fv_1		36.108	$N.s.m^{-1}$	3.81
Fv_2		89.419	$N.s.m^{-1}$	2.45
Fv_3		35.211	$N.s.m^{-1}$	6.34
Fv_4		64.793	$N.s.m^{-1}$	3.10

Observation matrix condition number: 355.56
Number of samples: 65404

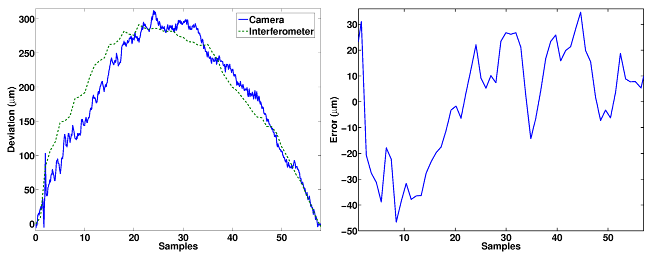
TABLE I
Dynamic identification results



(a) Calibration pattern and interferometer mounted on the end-effector

(b) Camera and laser

Fig. 7. *Straightness measure with an high speed camera and a laser interferometer*



(a) Deviation on Y-axis

(b) Error between laser interferometer and camera measures

Fig. 8. *Comparison between laser interferometer and camera*

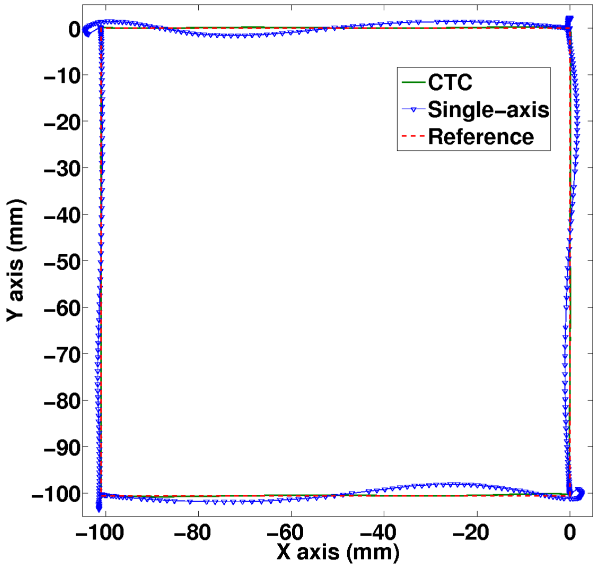


Fig. 9. *Comparison between single-axis and CTC controller measured with an high speed camera on a 100mm XY square*

	PID	CTC
Left edge	0.733mm	0.154mm
Right edge	2.255mm	0.330mm
Bottom edge	3.318mm	0.443mm
Top edge	3.143mm	0.293mm

TABLE II

Measured straightness error on square segment with an high speed camera

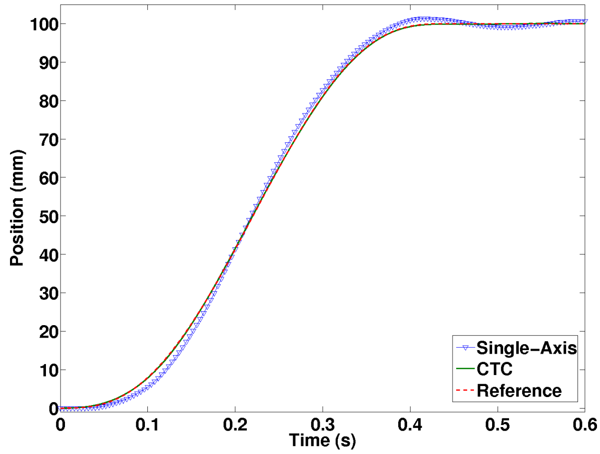


Fig. 10. *Tracking error on X axis measured with an high speed camera on a 100mm square*

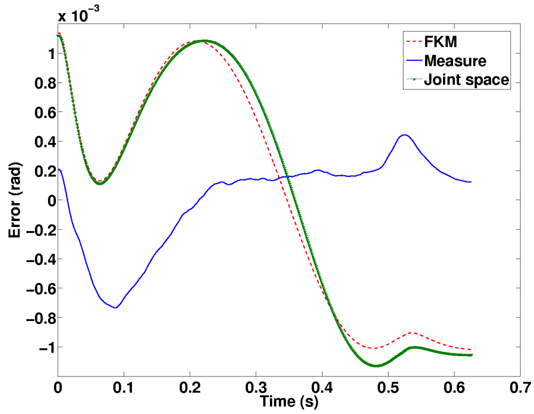


Fig. 11. *Orientation tracking error with a computed torque control in the joint and the Cartesian space, with Forward Kinematics and direct measure*

in the single-axis controller can not be set at the theoretical value because the linear actuators we use do not cope with noise, even filtered. Figure 9 shows a comparison between single-axis and computed torque controls. The reference trajectory is a simple 100 mm square in the XY frame. A fifth degree path generation with a $3m.s^{-2}$ maximal acceleration is used. The trajectory is executed segment by segment.

According to Figure 9, computed torque control in the joint space achieves an accurate tracking while the single-axis can not. Numerically, the straightness error are divided by 7 for X-axis displacement and 10 for Y-axis displacement (see Table II). Furthermore, there is no overshoot at the end of travel with the computed torque control (see Figure 10). Thus, using computed torque control instead of a linear single-axis control improves tracking, even in the joint space. Indeed, due to heavy inertia, the dynamic coupling between legs is not neglectable even at $3m.s^{-2}$. Consequently, the dynamic behaviour of the machine should be compensated for to improve accuracy.

At the moment, we are not able to propose experiments on a control with a direct measure of the end-effector pose. Nevertheless, we propose a simulation to compare a joint space computed torque control, a Cartesian space computed torque control using the forward kinematics and one using a direct measure of the end-effector pose. Realistic noise is applied. The joint sensors have a $1\mu m$ accuracy. The direct measure has a $50\mu m$ and $0.001rad$ accuracy. The geometrical errors are fixed to $50\mu m$ and the dynamic parameters errors to 10%. In the Isoglide-4 T3R1 case, the geometrical errors have a great influence on the orientation estimation (see Eq 1). Consequently, the comparison is achieved on a 30° rotation of the end-effector. According to the Figure 11, the improvement between joint space and Cartesian space control with the forward kinematics is small since the Cartesian and joint reference are in a very close relation (see Eq 1). On the opposite, the use of a direct measure greatly improves the tracking even with a less accurate end-effector pose sensor than the joint one ($50\mu m$ against $1\mu m$). Indeed, the orientation measure leads to a better compensation of the dynamics since the measure is closer to the real orientation than the estimated one.

On the whole, these simulation and experiment results show three major points. First, using computed torque control instead of a linear single-axis control improves accuracy especially on heavy parallel kinematic machines like the Isoglide-4 T3R1. Second, the Cartesian space control improves the Cartesian reference tracking. Third, a direct measure of the end-effector pose, instead of an estimation with the Forward Kinematics, leads to better tracking since the geometrical errors have no influence on the feeback.

V. Conclusion

In this paper a discussion on parallel kinematic machine dynamic control was proposed. It showed that performing a computed torque control in the Cartesian space is relevant for parallel kinematic machine. According to the presented results, this control improves accuracy by compensating for the dynamic behaviour of the machine. However, there are two limitations. First, the dynamic model included in control has to depend on the end-effector. Second, the end-effector pose and velocity are needed. Generally, the latter are estimated with numerical models. It results in a lack of accuracy, computation time and reliability of the estimation. A first solution is metrological redundancy with proprioceptive measures to reduce the complexity of forward models and the number of solutions. However, accurate modeling and identification are still required. A second solution is a direct end-effector pose measure, with a laser tracker or vision for instance, which seems more promisefull

References

[1] J.P. Merlet. *Parallel robots*. Kluwer Academic Publishers, 2000.

[2] J. Tlusty, J. Ziegert, and S. Ridgeway. Fundamental comparison of the use of serial and parallel kinematics for machine tools. *Annals of the CIRP*, 48(1):351–356, 1999.

[3] J.P. Merlet. Still a long way to go on the road for parallel mechanisms. In *ASME 27th Biennial Mechanisms and Robotics Conference*, Montreal, Quebec, October 2002.

[4] B. Denkena and C. Holz. Advanced position and force control concepts for the linear direct driven hexapod PaLiDa. In *The fifth Chemnitz Parallel Kinematics Seminar*, pages 359–378, Chemnitz, Germany, April 2006.

[5] C. Brecher, T. Ostermann, and D.A. Friedich. Control concept for PKM considering the mechanical coupling between actuators. In *The fifth Chemnitz Parallel Kinematics Seminar*, pages 413–427, Chemnitz, Germany, April 2006.

[6] H. Chanal, E. Duc, and P. Ray. A study of the impact of machine tool structure on machining processes. *International Journal of Machine Tools and Manufacture*, 46:98–106, 2006.

[7] H. Abdellatif and B. Heiman. Adapted time-optimal trajectory planning for parallel manipulators with full dynamic modeling. In *International Conference on Intelligent Robots and Systems (IROS'05)*, pages 411–416, Barcelona, Spain, April 2005.

[8] W. Khalil and E. Dombre. *Modeling, identification and control of robots*. Hermes Penton Science, London-Paris, 2002.

[9] M. Callegari, M.C. Palpacelli, and M. Principi. Dynamics modelling and control of the 3-RCC translational platform. *Mechatronics*, 16:589–605, 2006.

[10] A. Vivas. Predictive functionnal control for a parallel robot. *IEEE International Conference on Intelligent Robots and Systems (IROS'03)*, pages 2785–2790, October 2003.

[11] J. Kövecses and J.C. Piedboeuf. Methods for dynamic models of parallel robots and mechanisms. In *Workshop on Fundamental Issues and Future Research Directions for Parallel Mechanisms and Manipulators*, pages 339–347, Quebec, Canada, October 2002.

[12] S.H. Lee, J.B. Song, W.C. Choi, and D. Hong. Position control of a Stewart platform using inverse dynamics control with approximate dynamics. *Mechatronics*, 13:605–619, 2003.

[13] J. Wang and O. Masory. On the accuracy of a stewart platform - part I: the effect of manufacturing tolerances. In *IEEE International Conference on Robotics and Automation (ICRA'93)*, pages 114–120, Atlanta, USA, May 1993.

[14] M.M. Olsen and H.G. Peterson. A new method for estimating parameters of a dynamic robot model. *IEEE Transactions on Robotics and Automation*, 17(1):95–100, 2001.

[15] B. Dasgupta and P. Choudhury. A general strategy based on the newton-euler approach for the dynamic formulation of parallels manipulators. *Mechanism and Machine Theory*, 34:801–824, 1999.

[16] G. Gogu. Fully-isotropic T3R1-type parallel manipulators. In J. Lennarčič and B. Roth, editors, *On Advances In Robot Kinematics*, pages 265–272. Kluwer Academic Publishers, 2004.

[17] K.J. Waldron and K.H. Hunt. Series-parallel dualities in actively coordinated mechanisms. *International Journal of Robotics Research*, 10(2):pp. 473–480, 1991.

[18] F. Paccot, N. Andreff, and P. Martinet. Revisiting the major dynamic control strategies of parallel robots. In *European Control Conference (ECC'07)*, Kos, Greece, July 2007. To appear.

[19] T. Dallej, N. Andreff, Y. Mezouar, and P. Martinet. 3d pose visual servoing relieves parallel robot control from joint sensing. In *International Conference on Intelligent Robots and Systems (IROS'06)*, pages 4291–4296, Beijing, China, October 2006.

[20] M.L. Husty. An algorithm for solving the direct kinematic of the Gough-Stewart platforms. Technical Report TR-CIMS-94-7, McGill University, Montréal, Canada, 1994.

[21] D. Chablat and P. Wenger. Working modes and aspects in fully parallel manipulators. In *IEEE International Conference on Robotics and Automation (ICRA'98)*, pages 1964–1969, Leuven, Belgium, May 1998.

[22] M. Zein, P. Wenger, and D. Chablat. Singular curves and cusp points in the joint space of 3-rpr parallel manipulators. In *IEEE International Conference on Robotics and Automation (ICRA'06)*, pages 777–782, Orlando, USA, May 2006.

[23] P. Dauchez, X. Delebarre, and R. Jourdan. Hybrid control of a two-arm robot handling firmly a single rigid object. In *2nd International Workshop on Sensorial Integration for Industrial Robots (SIFIR'89)*, pages 67–62, Zaragosa, Spain, November 1989.

[24] J.P. Merlet. Solving the forward kinematics of Gough-type parallel manipulator with interval analysis. *The International Journal of Robotics Research*, 23:221–235, 2004.

[25] L. Baron and J. Angeles. The direct kinematics of parallel manipulators under joint-sensor redundancy. *IEEE Transactions on Robotics and Automation*, 16(1):1–8, 2000.

[26] http://www.faro.com.

[27] W.S. Newman, C.E. Birkhimer, R.J. Horning, and A.T. Wilkey. Calibration of a motoman p8 robot based on laser tracking. In *IEEE International Conference on Robotics and Automation (ICRA'00)*, pages 3597–3602, San Francisco, USA, April 2000.

[28] S. Hutchinson, G. Hager, and P. Corke. A tutorial on visual servo control. *IEEE Transactions on Robotics and Automation*, 12(5):651–670, 1996.

[29] R. Ginhoux, J. Gangloff, M.F. de Mathelin, L. Soler, M. Arenas Sanchez, and J. Marescaux. Beating heart tracking in robotic surgery using 500 hz visual servoing, model predictive control and an adaptative observer. In *IEEE International Conference on Robotics and Automation (ICRA'04)*, pages 274–279, April, New Orleans, USA 2004.

[30] F. Paccot, N. Andreff, P. Martinet, and W. Khalil. Vision-based computed torque control for parallel robots. In *The 32nd Annual Conference of the IEEE Industrial Electronics Society (IECON'06)*, pages 3851–3856, Paris, France, 7-10 November 2006.

[31] W. Khalil and O. Ibrahim. General solution for the dynamic modeling of parallel robots. In *IEEE International Conference on Robotics and Automation (ICRA'04)*, pages 3665–3670, New Orleans, USA, April 2004.

[32] S. Guegan, W. Khalil, and P. Lemoine. Identification of the dynamic parameters of the Orthoglide. In *IEEE International Conference on Robotics and Automation (ICRA'03)*, pages 3272–3277, Taipei, Taiwan, September 2003.