12th IFToMM World Congress, Besançon, June 18-21, 2007

Enhancing tracking performances of parallel kinematic machines

Flavien Paccot* Nicolas Andreff† Philippe Martinet‡
LASMEA LAMI/LASMEA IRSC/LASMEA
Aubière, France Aubière, France Suwon, South Korea/Aubière, France

Abstract— *In pratice, parallel kinematic machines are not always as accurate as expected. Consequently , we propose a discussion on methods improving the tracking performances. It is shown that a Cartesian space Computed Torque Control, associated with an adapted dynamic model and a good identification, is particularly relevant for parallel kinematic machines. Experimental results show that improvements in tracking performances can be noticed even at machining speeds, yet considered as quasi-static.*

Keywords: Parallel Kinematic Machines, Dynamic modeling, Dynamic control, Dynamic identification

I. Introduction

Last years trend, parallel kinematic machines are spreading in industry. Indeed, their stiffness, accuracy, high speed and high load capacities are generally admitted [1]. Consequently, parallel kinematic machines seem to be perfectly suitable for two major applications: High Speed Machining and pick-and-place. Considering the latter, recent demonstrators, like the PAR4, allow for a $170 m.s^{-2}$ maximal acceleration [2]. However, the experience shows that parallel kinematic machines are not as accurate as expected, especially in High Speed Machining [3]. Indeed, the accuracy is limited by the presence of numerous joints and assembly errors [4]. This issue is generally improved by a kinematic identification which ensures reaching a desired position in the Cartesian space with accuracy [1], [5]. As machining operations are generally supposed to be quasi-static, a simple linear single-axis control associated with a good kinematic identification is often considered as sufficient for the required accuracy, thus increasing the effects of small accelerations. Nevertheless, speeds and accelerations currently used during machining processes are not negligible: $20 m.min^{-1}$ and $3 m.s^{-2}$. In addition, machines are heavy since an important stiffness is required. Consequently, can the machining process still be considered as quasi-static? If not, the control schemes have to be improved to ensure a better tracking.

Indeed, the dynamic behaviour of a parallel kinematic machine is complex and non-linear [1], [6]. Firstly, it depends, in most cases, on the pose of the end-effector, also called mobile platform. Actually, it has been shown that the kinematics of most parallel kinematic machines are only defined by the end-effector pose and velocity [7]. By extrapolating this property, the dynamics can be defined by the end-effector pose, velocity and acceleration. Secondly, due to the closed kinematic structure, a dynamic coupling between legs exists. Consequently, a linear single-axis control can not compensate for the machine dynamic behaviour with homogeneous efficiency [8]. Actually, a linear PID controller with constant gains ensures good performances with linear systems, which is only achieved very locally for the dynamics of a parallel kinematic machine. Therefore, it results in a lack of tracking accuracy except in a small part of the work space, already small for a parallel kinematic machine. Many solutions considering the dynamics are proposed like non-linear controller gains or non-linear feedforward [9], [10]. However, the dynamic decoupling is not ensured, making the behaviour still non-linear. In addition, the machine effective motion represents a disturbance, thus imposing robust techniques to ensure good accuracy and stability [9]. In this way, the well-known Computed Torque Control is a direct way to take into account the dynamic behaviour and to ensure a complete dynamic decoupling [11]. Nevertheless, this control scheme is occasionally used for parallel kinematic machines. In fact, several numerical transformations are used as developed further down, thus degrading stability and accuracy. In addition, dynamic modelling errors generate disturbances leading to instabilities [11]. In this case, robust techniques can be employed, like predictive or H_∞ control [12], [13]. A lighter way can be the use, in a first time, of a good dynamic model and a dynamic identification.

Actually, dynamic modeling errors come from different sources: unmodeled phenomena, frictions or complexity of the assembly for instance. A dynamic identification allows for minimizing the modeling errors influence [14], [15]. Furthermore, the modeling method choice is important in a control context. It is generally admitted that a Newton-Euler based method is more adapted for control since it requires less computation than Lagrange based methods [16], [6]. In addition, in most cases met in literature, the dynamic model is written as a function of the joint variables and their time derivatives, contradicting assertions above. Therefore, transformations between joint space and Cartesian space are implicitly included in the model. Frequently, these transformations have not a closed-form expression for the parallel kinematic machine contrary to the serial one.

*E-mail: Flavien.Paccot@lasmea.univ-bpclermont.fr
†E-mail: Nicolas.Andreff@ifma.fr
‡E-mail: Philippe.Martinet@lasmea.univ-bpclermont.fr

It enters into the difficulties of numerical estimation such as numerical stabilities, accuracy and reliability. Consequently, improving accuracy and stability of a Computed Torque Control can be first achieved by decreasing computation with an adapted modeling and a dynamic model written as a function of the end-effector pose. Nevertheless, the latter is only useful with a control in the Cartesian space with the advantages and drawbacks explained in further paragraphs.

In this paper, we propose a reformulation of a recent dynamic modeling method. We show that the obtained model can be expressed as a function of the end-effector pose and its time derivatives. The method is then applied to a parallel kinematic machine with decoupled motion, the Isoglide-4 T3R1 [17]. A second contribution is a discussion on the dynamic control of parallel kinematic machines. We show that a Computed Torque Control in the Cartesian space is perfectly relevant for these machines. Finally, experimental results are provided. First results concern the dynamic identification of the Isoglide-4 T3R1. Then, a comparison between a linear single axis control and a Computer Torque Control is proposed.

This article is organized as follow: Section II deals with dynamic modeling, Section III concerns control, Section IV presents the Isoglide-4 T3R1 and its dynamic model and Section V gives experimental results.

II. Dynamic modeling

Achieving a performant dynamic control requires an adapted inverse dynamic model. In this way, Khalil proposes a modeling method suitable for control and working in the general case [6]. It consists of expressing in the active joints both the contribution of each leg dynamics, considered as simple stand-alone serial kinematic machines, and the end-effector dynamics. However, the approach expresses the model in the joint motions entering into the difficulties of numerical estimation listed above. In fact, the Inverse Dynamic Model can be formulated as:

$$\Gamma(X,\dot{X},\ddot{X}) = \underbrace{D_{inv}^{-T}(X)F_p(X,\dot{X},\ddot{X})}_{\substack{\text{Contribution of the}\\ \text{end}-\text{effector}}} + \sum_{i=1}^{n} \underbrace{D_{inv}^{-T}(X)J_{pi}^T(X)J_i^T(q_i)H_i(q_i,\dot{q}_i,\ddot{q}_i)}_{\substack{\text{Contribution of}\\ \text{each leg}}} + \Gamma_f \tag{1}$$

where Γ are the active joint torques or forces.

The first term in this expression concerns the dynamic behavior of the end-effector ($F_P(X,\dot{X},\ddot{X})$, which trivially depends only on the end-effector motion). It is projected onto the active joints via the Inverse Instantaneous Kinematic matrix ($D_{inv}(X)$). This matrix depends only on the end-effector pose [7]. Then, the projection of the dynamics of each leg ($H_i(q_i,\dot{q}_i,\ddot{q}_i)$), seen as a single serial machine, onto the active joints is realized. H_i is first projected in the link between leg i and the end-effector with the Inverse Instantaneous Kinematic matrix of the leg ($J_i(q_i)$). Then, the result is expressed in the end-effector frame with the Jacobian matrix ($J_{pi}(X)$), linking the Cartesian coordinates of the end-effector to the Cartesian coordinates of the terminal point of the leg i. And finally, it is projected in the active joint space with $D_{inv}(X)$. The last term, Γ_f, concerns friction depending on active joint variables in the general case.

At first glance, this model does not depend only on the end-effector pose. However, in most cases, parallel robots have quite simple legs with few joints (three or four). Thus, linking passive joint variables to the end-effector pose is easy with trivial trigonometry. Furthermore, the active joint variables are linked to the end-effector pose with the algebraic Inverse Kinematic Model depending on the end-effector pose. Consequently, each term depends algebraically on the end-effector pose. In most cases, this method should lead to an Inverse Dynamic Model suitable for Cartesian space Computed Torque Control.

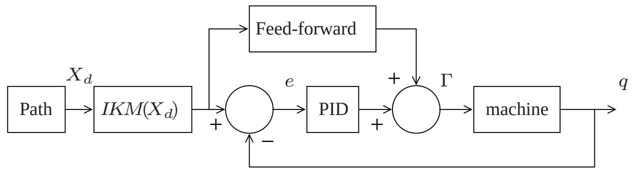


Fig. 1. *Single-axis control with PID controller and feed-forward*

III. Dynamic control

In most cases, industrial parallel kinematic machines use a linear single-axis control with PID controller and feed-forward (see Figure 1). The implementation of this control is easy. Tuning of the constant gains is well-known. Such a controller can be used as well for serial kinematic machines as for parallel ones. Consequently, there is no improvement of skills required to ensure a correct maintenance. Furthermore, accuracy is acceptable. Thus, this controller is widespread in the industry.

However, a parallel kinematic machine has a non-linear dynamic behaviour. Therefore, the dynamic behaviour is not compensated for with a constant efficiency along the whole workspace [8]. It results in a lack of accuracy, increasing with speed.

There are lots of methods including machine dynamics in the control scheme, to increase accuracy. The most direct way to compensate for the machine dynamic behavior is to include it in the control loop. The so-called Computed Torque Control is widespread for serial manipulators. It encloses an Inverse Dynamic Model depending on joint positions, speeds and accelerations (see Figure 2 and [11]). Notice that, in this case, $\widehat{IKM}$ is a numerical solution to the inverse kinematic problem, obtained by numerical inversion of the closed-form forward kinematic model.

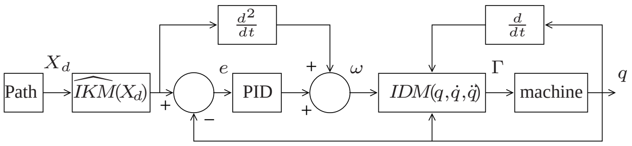


Fig. 2. *Joint space Computed Torque Control for serial kinematic machines*

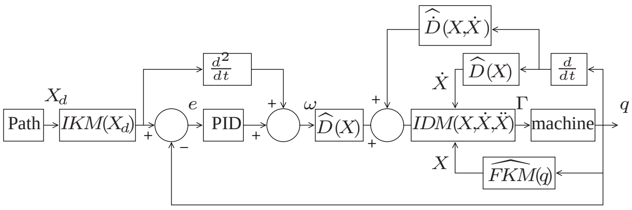


Fig. 3. *Joint space Computed Torque Control for parallel kinematic machines*

This control ensures excellent tracking performances with a perfectly identified model. However, its transposition to parallel kinematic machines is harder than for the linear single-axis controller. Computed Torque Control of parallel machine met in literature is generally done in the joint space, since actuator encoders are the only reliable and accurate measure [12]. Thus, numerical transformations from joint space to Cartesian space are required leading to a complex control scheme (see Figure 3). By considering the numerical estimation issues, one can easily understand why the Computed Torque Control is rarely used for parallel kinematic machines.

In order to reduce the control scheme complexity, we propose here to use a *Cartesian space Computed Torque Control* (see Figure 4). In this case, two numerical transformations are removed from the control scheme in Figure 3. Computation cost gains allow for a faster and a more accurate control. In addition, trajectories are planned in the Cartesian space, which is usually the user's task space. Thus, a Cartesian space control is more natural. Moreover, Cartesian space control is adapted for parallel kinematic machine according to the following structural considerations. Firstly, a better end-effector trajectory tracking is ensured. Indeed, one joint variables configuration may lead to several end-effector poses [18], [19]. 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 or on cuspidal machines [20]. After such a disturbance, the Cartesian space control brings back the end-effector to its reference Cartesian trajectory contrary to joint space control (see Figure 5).

Secondly, servoing each actuator separately can create parasite moves conflicting with end-effector moves. Two types of defaults appear, uncontrolled parasite end-effector moves or internal torques if these moves are impossible, degrading passive joints. Like two-arms machine control,

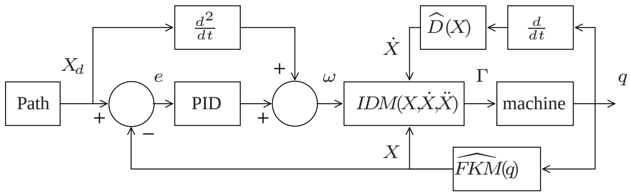


Fig. 4. *Cartesian space Computed Torque Control for parallel kinematic machines*

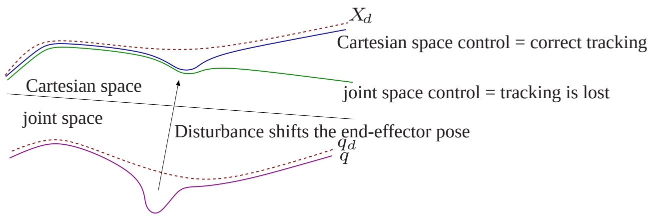


Fig. 5. *Cartesian space ensures correct end-effector reference tracking contrary to joint space control*

Cartesian space control can minimize, or cancel in the best cases, internal torques [21]. Consequently, Cartesian space control is particularly relevant for parallel kinematic machines.

Nevertheless, these advantages are only conceivable with a reliable measure of the end-effector pose and velocity. The technological advances make such a measure realistic in a near future [22]. At the moment, the presence of Forward Kinematics and Instantaneous Kinematics in the control scheme is the main issue making Cartesian space control use occasional. Nevertheless, in a few of cases, parallel kinematic machine have closed-form Forward Kinematics or Instantaneous Kinematics, like the Isoglide-4 T3R1. In these cases, the Cartesian space control can be employed easily. In the other cases, several works propose algorithm for the Forward Kinematic Model [18], [23]. Otherwise, the metrological redundancy can be used to decrease Forward Kinematics complexity and the number of solutions [24].

IV. Application to the Isoglide-4 T3R1

A. Machine description

To validate the above discussions, we propose to apply the proposed modeling and control scheme to the Isoglide-4 T3R1. This parallel kinematic machine is a fully-isotropic one with decoupled motion (see Figure 6 and [17]). 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. A desired maximum acceleration of $20m.s^{-2}$ associated with heavy weight creates an important dynamic coupling between the legs. This test-bed is well suited to the validation of the approach, since its weight prevents us from neglecting the dynamics. Moreover, its closed-from kinematic models remove from the control problem the troubles

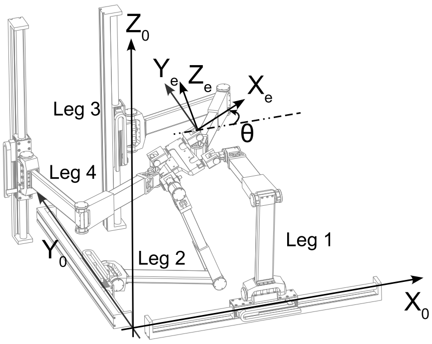


Fig. 6. *Global view of the Isoglide-4 T3R1*

associated to kinematic non-linear couplings [25]. They also compensate for the current technological lack of reliable and accurate high-speed sensor of the end-effector pose.

B. Dynamic model

The modeling method presented in Section II is applied to the Isoglide-4 T3R1. A closed-form model is obtained. As the global expression is huge, only the main terms of Equation 1 are given. The first term concerns the end-effector:

$$F_P(X,\dot{X},\ddot{X}) = \begin{bmatrix} M_P\ddot{X}_e + M_PX_P\left(s_\theta\ddot{\theta} - c_\theta\dot{\theta}^2\right) \\ M_P\ddot{Y}_e \\ M_P\left(\ddot{Z}_e - g\right) - M_PX_P\left(c_\theta\ddot{\theta} + s_\theta\dot{\theta}^2\right) \\ YY_P\ddot{\theta} + M_PX_P\left(s_\theta\ddot{X}_e - c_\theta\ddot{Z}_e + s_\theta g\right) \end{bmatrix} \quad (2)$$

where M_P is the platform mass, M_PX_P is the first moment around X axis, g is the acceleration of gravity and $s_\theta = \sin\theta$.

Then, the second term concerns the inverse dynamic model of the leg i (see Figure 7 for details):

$$H_i(q_i,\dot{q}_i,\ddot{q}_i) = \begin{bmatrix} MR_1\ddot{q}_{1i} \\ ZZR_2\ddot{q}_{2i} + MXR_3d_3\left(c_{3i}\ddot{q}_{2i3i} - s_{3i}\dot{q}_{2i3i}^2\right) \\ ZZR_3\ddot{q}_{2i3i} + M_4d_4d_3\left(c_{3i}\ddot{q}_{2i} + s_{3i}\dot{q}_{2i}^2\right) \end{bmatrix} \quad (3)$$

where MR_1 is the mass of the leg, q_{ji} are the joint variable ($q_{1i} = q_i$ are the active joint variables), $q_{jiki} = q_{ji} + q_{ki}$, ZZR_2 and ZZR_3 are the inertia of the arms and the forearms, M_4 is the mass of the fourth body, d_3 and d_4 are the length of the arms and the forarms.

In Equation 3, the gravity influence is not mentioned. The latter can be expressed as :

$$\begin{array}{c} g[0\ (M_4+M_3)d_3s_{21}\ M_4d_4s_{2131}]^T \text{ for leg 1} \\ g[0\ (M_4+M_3)d_3c_{22}\ M_4d_4c_{2232}]^T \text{ for leg 2} \\ g[-MR_1+Mcomp_i\ 0\ 0]^T \text{ for leg 3 and 4} \end{array} \quad (4)$$

where M_3 is the mass of the third body, $Mcomp_i$ is the influence of gravity compensators mounted onto legs 3 and 4.

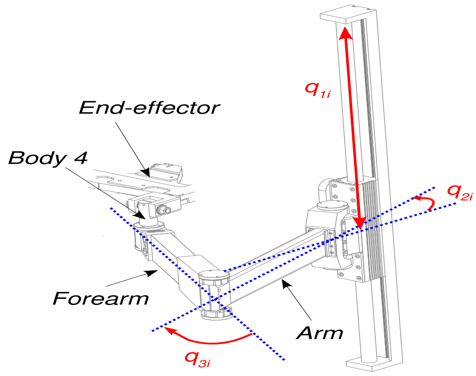


Fig. 7. *Details of one leg*

V. Experimental results

A. Dynamic Identification

In order to minimize the influence of modeling errors, a dynamic identification is realized (See [14]). The exciting trajectory is composed of fifth degrees linear motion axis by axis, with accelerations ranging from 0.5$m.s^{-2}$ to 5$m.s^{-2}$. By considering the structure of the Isoglide-4 T3R1, this trajectory seems to be sufficiently exciting. Indeed, the torques recorded on a moving axis allow for estimating inertia of the concerned legs. The torques recorded on steady axis allow for determining the remaining terms. In additions, frictions are estimated at low speed since they are preponderant. Table I summarize the results of the identification process. Parameters are identified with closeness with a relative standard deviation of 0.43% to 5.9%. Let us remark that two parameters, M_PX_P and YY_P, are not identified. In fact, the end-effector is lighter than the legs, thus having little influence on dynamics at used accelerations. In addition, the term MXR_3 can not be estimated since it has nearly the same influence as ZZR_3 and ZZR_2 parameters. Thus, seperating each influences is difficult. A wider range of accelerations can be an answer. However, for design issues, it is impossible at the moment.

B. Dynamic control

To emphasize the improvement of dynamic control over linear single-axis control, a translation straightness measure is performed with a 512×512 camera as exteroceptive measure running at $250Hz$. This provides us with a measure of the end-effector trajectory instead of an estimation tainted with modeling error and deformations. In order to prove the camera accuracy, a comparison between the latter and a laser interferometer is proposed (See Figure 8). According to Figure 9, the camera has an average accuracy of 26μm validating further results.

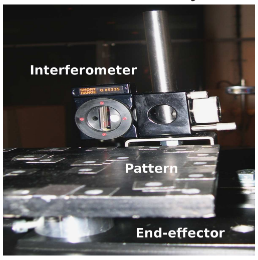
For a fair comparison, both the single-axis and Computed

Parameter	CAD values	Identified values	Units	$\sigma(\%)$
MXR_3	3.235	0	$kg.m$	
ZZR_3	1.787	1.0213	$kg.m^2$	3.3182
ZZR_2	4.642	4.3601	$kg.m^2$	0.7069
M_4	1.181	0.6808	kg	2.5695
M_3	7.053	8.2193	kg	0.5115
M_t	45.011	45.2624	kg	0.5308
M_{R1}	31.4380	43.2893	kg	0.4296
M_PX_P	2.059	0	$kg.m$	
YY_P	0.411	0	$kg.m$	
$Mcomp_3$		45.9606	kg	0.5256
$Mcomp_4$		35.2540	kg	0.5457
Fs_1		7.8167	N	5.8923
Fs_2		17.4868	N	3.3235
Fs_3		14.7795	N	3.9876
Fs_4		24.8595	N	1.8696
Fv_1		43.4432	$N.s.m^{-1}$	3.8255
Fv_2		117.0161	$N.s.m^{-1}$	2.3587
Fv_3		58.1136	$N.s.m^{-1}$	4.8226
Fv_4		79.5603	$N.s.m^{-1}$	3.0498

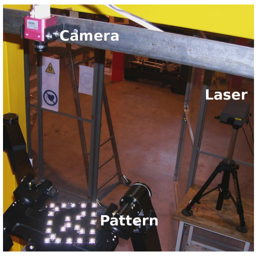
Observation matrix condition number: 398.7728

Number of samples: 16351

TABLE I. *Dynamic identification results*

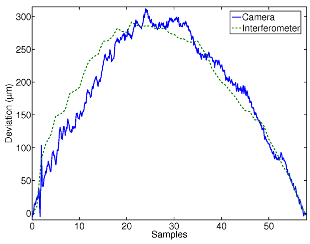


(a)Calibration pattern and interferometer mounted on the end-effector

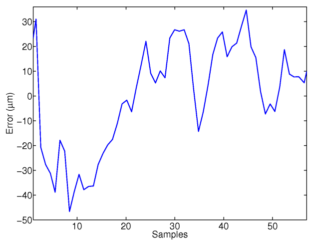


(b)Camera and laser

Fig. 8. *Straightness measure with an high speed camera and a laser interferometer*



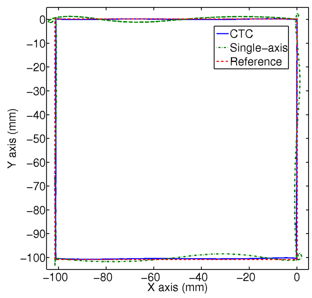
(a)Deviation on Y-axis



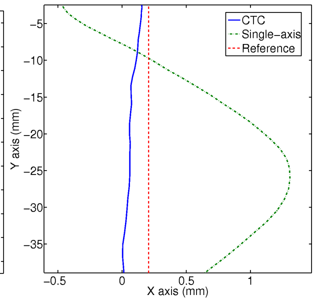
(b)Error between laser interferometer and camera measures

Fig. 9. *Comparison between laser interferometer and camera*

Torque control schemes have the same gain tuning with same cut-off frequency (ω_c) of $5Hz$. Nevertheless, derivative gains in the single-axis controller can not be set at the theoretical value because the linear actuators do not cope with noise, even filtered. Figure 10 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 $3m.s^{-2}$ maxi-



(a)Global view



(b)Zoom

Fig. 10. *Comparison between single-axis and CTC controller measured with an high speed camera on a 100mm XY square*

	single-axis	CTC
Segment 1	733	154
Segment 2	2255	330
Segment 3	3318	443
Segment 4	3143	293

TABLE II. *Measured straightness in μm on square segment with an high speed camera*

mal acceleration is used. The trajectory is executed segment by segment. According to Figure 10, it can be noticed that great improvements are realized. Indeed, due to heavy inertia, the dynamic coupling between legs is not negligible even at $3m.s^{-2}$. Using Computed Torque Control improves tracking, straightness errors are divided by 7 for X-axis displacements and 10 for Y-axis displacements (see Table II where segment 1 is the left edge of square, segment 2 the right edge, segment 3 the bottom edge and segment 4 the top edge). Furthermore, there is no overshoot at the end of travel with the Computed Torque Control (see Figure 10).

It can be noticed that the trajectory is followed with typical high speed machining accelerations. Consequently, it seems that machining can not be considered as quasi-static for a heavy parallel kinematic machine, even with simple structure. With a 100μm maximal tolerance on straightness as generally required in machining, a linear single-axis control is unsuitable. However, the Computed Torque Control used above does not improve enough the straightness. Nevertheless, this seems be attributable to defects on structure and assembly. To prove it, we propose a simulation without taking into account these defects, with realistic noise on dynamic parameters (10%) and measure (1μm with used encoders). Simulated and experimental behaviours are similar but values are smaller in simulation. In this case, we focus only on the control scheme. We propose to study the influence of the speed on straightness. Simulation shows that a linear single-axis control can not ensure a 100μm straightness above a $1m.s^{-2}$ acceleration, contrary to the Computed Torque Control which ensures a 78μm straightness under a $20m.s^{-2}$ acceleration (See table III). It seems that High Speed Machining process imposes a Computed Torque Control to meet tolerance requirements. Nevertheless, Figure 11 shows the influence of acceleration on inertia, dynamic coupling on moving and steady legs and fric-

Acceleration ($m.s^{-2}$)	0.5	1	5	10	20
Single-axis	55	124	758	1520	3483
CTC	11	12	20	31	78

TABLE III. *Simulated straightness in μm for segment 1*

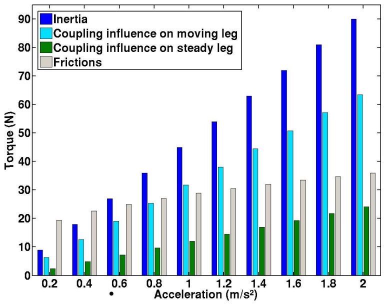


Fig. 11. *Influence of acceleration on different dynamic phenomena*

tions. This allows us to nuance our assertions. In fact, frictions are not negligible at such speeds. Moreover, their modeling is difficult at low speed. Consequently, we can not ensure that our dynamic model is efficient at such low speed.

VI. Conclusion

In this paper, we propose a discussion on how to enhance tracking performances of parallel kinematic machine through adapted control schemes. The well known Computed Torque Control brings great improvements on accuracy. We show that the latter is particularly relevant for parallel robot when it is performed in the Cartesian space, associated with adapted modeling and good identification. Experiments show that improvements are noticed even at high speed machining speeds, even considered as quasi-static. Nevertheless, our study has to be deepened. Firstly, a better friction model has to be employed, especially at low speed. In addition, frictions in passive joints can be considered. Secondly, structure and assembly defects can be taken into account in the control schemes either in a more complex Forward Kinematic Model [25] or by replacing this model by an exteroceptive measure. In the latter case, the influence of these defects on dynamics have to be studied.

VII. Acknowledgements

This work was supported by European Community through the IP projet NEXT number 0011815.

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