Estimation of absolute orientation for a bipedal robot: experimental results

Vincent Lebastard, Yannick Aoustin, and Franck Plestan

***Abstract*—This paper deals with the estimation, during the imbalance phases of a walking cyclic gait, of the absolute orientation of a planar biped by only using the measurement of the actuated joint variables. The main contribution is the experimental evaluation of an original finite-time convergent posture observer which allows to get an accurate estimation, in finite time and in spite of the uncertainties and perturbations.**

***Index Terms*—Bipedal robot, finite time observer, experimentation.**

I. INTRODUCTION

The control of bipedal robots is Generally founded on the dynamic model [6], [1], [17]. Then, the state knowledge is required. But, it is quite difficult in imbalance phases to measure the absolute orientation of a biped. Furthermore, problems such as bandwidth limits, offset errors, robustness or financial cost have to be taken into account in the design of biped structure: in fact, measurements of the whole state vector imply the use of sensors as accelerometers, gyrometers, inertial units, potentiometers.

Encoders sensors or resolver sensors directly attached to the motor shaft are efficient to determine the joint variables of a robot, and their precision is improved in presence of gearbox reducers. These advantages entail to explore observers able to estimate the state vector during the imbalance phases from only the knowledge of the joint variables.

Few results have been published for the design of such observers where a lot of works have focused on observers design for the estimation of velocities only. For example, in [7], an original reduced observer has been designed by introducing a new state, which is the sum of the velocities state and the configuration variables, adjusted by a scalar gain. In [13], a pose estimator for a walking hexapod robot has been designed. This estimator needs that at least three legs remain in ground contact at all times, and is using the outputs of 6 leg-configuration sensor models together with *a priori* knowledge of the ground and robot kinematics to compute estimates of the 6 DOF body pose. Using the joint angle as measured output, a Kalman filter is proposed by [14] for the estimation of joint rate to control the in-between leg only of a compass robot in single support. However, a such estimation algorithm has two drawbacks. The computation cost is heavy. Furthermore, it does not allow a formal proof of stability of the closed-loop system. A such stability proof has been proposed in [10], [11]: in the both papers, it has been made by using a finite-time convergence observer coupled to a finite-time convergence controller. These convergence properties allow to simplify the stability proof. The observers used in [10], [11] are based on high order sliding mode [5], which allows to reduce the well-known *chattering* phenomenon while robustness and finite time convergence features are maintained. In [10], the observer based on *twisting* algorithm [12] requires the knowledge of joints positions and velocities. It implies the use of differentiators amplifying the noise in the control input. The observer in [11] is based on high order sliding mode time differentiators.

The paper proposes a new version of high order sliding mode observer based on *super twisting* approach [12] in order to estimate the absolute orientation of a five-link biped without feet during a walking gait. This class of observer is using only measurements of the joint variables, and not their time derivatives which implies less noise in the controller. It yields that the originality of the current paper is found in the nature of the observer (robustness and finite-time convergence) and its experimental evaluation. This robustness is required given that the observer synthesis is based on an “ideal” model, supposing that the biped is evolving in a single plane, the impact is instantaneous and the parameters are well-known. The paper is organized as follows: the biped’s model is presented in Section II. Section III is devoted to the observation problem and the observer design. Section IV details experimental results.

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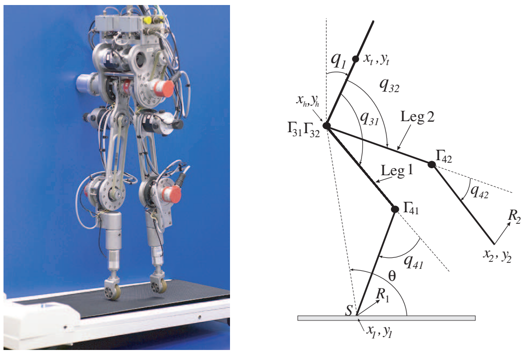
II. MODEL OF THE BIPED ROBOT *RABBIT*

The prototype *Rabbit* [3] (Figure 1) has been designed as a simple mechanical anthropomorphic structure. It is composed of a torso and two identical double-link legs with knees. Both legs have no feet (point feet - see Figure 1-Left). *Rabbit*'s lateral stabilization is ensured by a rotating bar. The presence of this bar and wheels on the legs tips lead *Rabbit* to walk in a circular path. Only a 2D motion in the sagittal plane is considered. There are four electrical DC motors with gearbox reducers actuating hip joints and knee joints. From simulation, prototype characteristics (sizes, masses, inertia moments of the links) and adequate actuators have been chosen [3]. The actuators parameters are specified in Table I. Lengths, masses and inertia moments of each link are specified in Tables II. The maximal value of the torque of each motor gearbox is $150\ N \cdot m$. Each actuated joint is equipped with two encoders measuring the angular position. The first encoder sensor is attached to the motor shaft, while the second, an absolute encoder sensor is attached to the shaft of the gearbox reducer. An encoder sensor gives the angle of the torso with respect to a vertical axis established by the central column around which *Rabbit* is walking. This latter measurement will be compared to the estimated torso orientation. The bandwidth approximately equals 16 Hz for the joints mechanical part whereas it equals 1.7 kHz for the amplifiers. The contact between the leg tip and the ground is detected with a contact switch. The control/observation algorithm is implemented on a dSPACE system with a sample period equal to 1.5 ms (667 Hz).



(a) (b)

Fig. 1. (a). Photography of *Rabbit*. (b). Generalized variables and torques defined for *Rabbit* in the sagittal plane.

DC motor + gearbox	Hip	Knee
Length (m)	0.23	0.23
Mass (kg)	2.82	2.82
Gearbox ratio	50	50
Rotor inertia $(kg{\cdot}m^2)$	$3.25 \cdot 10^{-5}$	$2.26 \cdot 10^{-5}$
Electromagnetical constant torque $N{\cdot}m/A$	0.114	0.086
Rel. (incremental) encoder on shaft motor (count/rev)	250	250
Abs. encoder on the shaft of gearbox red. (count/rev)	8192	8192

TABLE I
ACTUATORS PARAMETERS

	Mass (kg)	Length (m)
Links 1 and 5: shin	$m_1 = m_5 = 3.2$	$l_1 = l_5 = 0.4$
Links 2 and 4: hip	$m_2 = m_4 = 6.8$	$l_2 = l_4 = 0.4$
Links 3: torso + actuators for knee and hip joints	$m_3 = 17.0$	$l_3 = 0.625$
	Center of mass locations (m)	Moment of inertia around the center of mass $(kg{\cdot}m^2)$,
Links 1 and 5: shin	$s_1 = s_5 = 0.1270$	$I_1 = I_5 = 0.10$
Links 2 and 4: hip	$s_2 = s_4 = 0.1630$	$I_2 = I_4 = 0.25$
Links 3: torso + actuators for knee and hip joints	$s_3 = 0.1434$	$I_3 = 2.22$

TABLE II
MECHANICAL PARAMETERS

A. Single-support model

Assuming that during the swing phase, the contact of the stance leg with the ground results in no rebound and no slipping, the dynamic model reads as

$$\begin{aligned} \dot{x} &= \begin{bmatrix} \dot{q} \\ D^{-1}(-H - G + B\Gamma) \end{bmatrix} \\ &= f(x) + g(q_{rel}) \cdot \Gamma, \end{aligned} \tag{1}$$

$q = \left[q_{rel}^T\ q_1\right]^T = \left[q_{31}\ q_{41}\ q_{32}\ q_{42}\ q_1\right]^T$. $D \in I\!R^{5\times 5}$ only depends on q_{rel}. $H(q, \dot{q}) \in I\!R^{5\times 1}$ is the Coriolis and centrifugal effects vector, and $G(q) \in I\!R^{5\times 1}$ the gravity forces vector. $B \in I\!R^{5\times 4}$ is a constant matrix. State vector x is $x = [q^T\ \dot{q}^T]^T$ and $q_{rel} := [q_{31}\ q_{32}\ q_{41}\ q_{42}]^T$. The state space is taken such that $x \in \mathcal{X} \subset I\!R^{10} = \{x = [q^T\ \dot{q}^T]^T \mid \dot{q} \in \mathcal{N},\ q \in \mathcal{M}\}$, $\mathcal{N} = \{\dot{q} \in I\!R^5 \mid |\dot{q}| < \dot{q}_M < \infty\}$, $\mathcal{M} = (-\pi, \pi)^5$.

B. Passive impact model

An impact occurs when

$$x \in \mathcal{S} = \{x \in \mathcal{X} \mid y_2(q) = 0\}$$

with $y_2(q)$ the altitude of the swing leg tip (see Figure 1). The impact is supposed passive and absolutely inelastic. The swing leg touching the ground does not slip and the previous stance leg takes off the ground. At the impact time T_I, there is a jump of the angular velocities. Given these hypotheses, the impact equation can be written [6] $x^+ = \Delta(x^-)$ with x^+ (resp. x^-) $:= [q^{+T} \; \dot{q}^{+T}]^T$ (resp. $[q^{-T} \; \dot{q}^{-T}]^T$) the state vector prior (resp. updated) the impact.

C. *Nonlinear model for entire step*

The overall biped model can be expressed as a system with impulse effects as [6]

$$\begin{array}{rcll} \dot{x} & = & f(x) + g(q_{rel})\Gamma, & \text{for } x^- \notin \mathcal{S} \\ x^+ & = & \Delta(x^-), & \text{for } x^- \in \mathcal{S}. \end{array} \quad (2)$$

III. Observer design

The objective is to estimate both biped robot posture and articular velocities from only joint variables measurement. An original observation approach is required due to loss of observability over one step.

A. *Observability analysis*

Consider the dynamical part of (1)

$$\dot{x} \;=\; f(x) + g(q_{rel})\Gamma \quad (3)$$

and define y the vector composed of the measured variables $h := [h_1 \; h_2 \; h_3 \; h_4]^T = q_{rel} \in I\!R^{4\times 1}$. This model is studied over one step, *i.e.* for $t \in [T_I^i, T_I^{i+1}[$, with T_I^i (resp. T_I^{i+1}) the initial (resp. final[1]) impact time of the step i. As $g(h)\Gamma$, the *input-output injection*[2] term of (3), is fully known, the observer for (3) will be *designed* by using

$$\dot{x} \;=\; f(x), \qquad h \;=\; [I_{4\times 4} \;\; 0_{4\times 6}]\, x \quad (4)$$

Definition [8] System (4) is uniformly observable if there exist an open set of $\mathcal{X}$, $\mathcal{T} \subset \mathcal{X}$ and 4 integers $\{k_1, k_2, k_3, k_4\}$, called *observability indices*, such that $\sum_{i=1}^{4} k_i \;=\; 10$ and the transformation $z = \Phi(x)$ defined as

$$\Phi(x) = \left[h_1 \cdots h_1^{(k_1-1)} \cdots h_4 \cdots h_4^{(k_4-1)} \right]^T \quad (5)$$

is a diffeomorphism for $x \in \mathcal{T}$. It yields

$$\text{Det} \left[\frac{\partial \Phi(x)}{\partial x} \right] \neq 0 \;\; \text{for } x \in \mathcal{T}. \quad (6)$$

■

Under the state transformation (5), system (4) reads as the so-called *observability canonical form*

$$\dot{z} \;=\; Az + \varphi(z) \quad , \quad h = Cz \quad (7)$$

with $A \;=\; \text{diag}\,[A_1 \; \cdots \; A_4]_{10\times 10}$, $C \;=\; \text{diag}\,[C_1 \; \cdots \; C_4]_{4\times 10}^T$, $\varphi(z) \;=\; [\varphi_1^T \; \cdots \; \varphi_4^T]^T$,

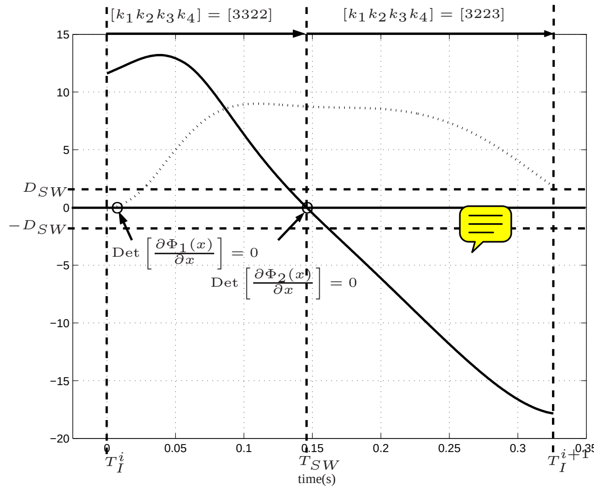


Fig. 2. Determinants of $\frac{\partial \Phi_1(\hat{x})}{\partial \hat{x}}$ (Bold line) and $\frac{\partial \Phi_2(\hat{x})}{\partial \hat{x}}$ (Dotted line) versus time (s.) over one step.

A_i, C_i and φ_i being under observability canonical form [9].

Loss of observability. Observability of (4) is analyzed from determinant of $\frac{\partial \Phi(x)}{\partial x}$ along biped trajectories over one step for different observability indices. Figure 2 displays this determinant in two cases, $[k_1 \; k_2 \; k_3 \; k_4]^T$ equals $[3\;2\;2\;3]^T$ (which gives $\Phi_1(x)$ from (5)), then $[3\;3\;2\;2]^T$ (which gives $\Phi_2(x)$ from (5)). For each case, there is *at least* one loss of observability over the step given that jacobian determinant is crossing zero[3].

B. *Observer structure and design*

The observation strategy consists in designing observers for several observability indices combinations, for which the observability singularity appears for different articular configurations. Define $\mathcal{T}_i$ $(i = \{1, 2\})$ as

$$\mathcal{T}_i \;=\; \left\{ x \in \mathcal{X} \mid \text{rank} \left[\frac{\partial \Phi_i}{\partial x} \right] \;=\; 10 \right\}$$

Let T_{SW} the smallest time instant such that $T_{SW} \;\in\; [T_I^i, T_I^{i+1}[$ and $\text{Det} \left[\frac{\partial \Phi_1(x)}{\partial x} \right] (T_{SW}) = 0$.

Proposition. [9] The observer for system (3) designed in the sequel reads as

$$\dot{\hat{x}} = f(\hat{x}) + g(h)\Gamma + M(y, \hat{x}, t) \quad (8)$$

[1]It implies that T_I^{i+1} is also the initial time of the step $i+1$.

[2]The use of input-output injection simplifying the system for the observer design does not change observability features [16].

[3]It would be possible to take an other choice for observability indice. But, for all cases, it can be numerically checked that the determinant is crossing zero during the step.

with

$$M = \begin{cases} \left[\dfrac{\partial \Phi_1(\hat{x})}{\partial \hat{x}}\right]^{-1} \chi_1(h, \hat{z}, t), t \in [T_I^i, T_{SW}[\\ \left[\dfrac{\partial \Phi_2(\hat{x})}{\partial \hat{x}}\right]^{-1} \chi_2(h, \hat{z}, t), t \in [T_{SW}, T_I^{i+1}[\end{cases}$$

and $\chi_1(\cdot)$ and $\chi_2(\cdot)$ appropriate-dimensional correction matrices. ■

The objective now consists in designing an observer, *i.e.* in finding the adequate function $M(h, \hat{x}, t)$, to ensure robustness and finite-time convergence. In fact, the robustness is a key-point given that hypotheses used for the model are quite restrictive but necessary for the both design of control and observer (for example, no friction and no elasticity appear in the model; the mass is supposed consists whereas the biped robot could be loaded by an added mass; It is supposed that the double support is instantaneous which is not the case by an experimental point-of-view). The finite time convergence allows to greatly simplify a formal analysis based on Poincaré's sections the stability of closed-loop system [10], [9], [11].
The observer algorithm is derived from [2] and its design is based on (7), which gives

$$\dot{\hat{z}} = A\hat{z} + \varphi(\hat{z}) + \underbrace{E(t) \cdot \Sigma(\cdot)}_{\chi(y, \hat{z}, t)} \tag{9}$$

with $\hat{z}$ the estimated vector of z. Knowing that the principle of this class of observers consists in forcing, each in turn, estimated state variables $\hat{z}_i$ to corresponding real ones z_i, in finite time, this latter property is obtained thanks to an adequate choice of $E(t)$ and $\Sigma(\cdot)$. The originality is the use of the *super twisting algorithm* [12] in $\chi(\cdot)$ to ensure the finite time algorithm: it allows to use no time derivative of estimation error. From (9) and inverse state transformations $\hat{x} = \phi_1^{-1}(\hat{z})$ and $\hat{x} = \phi_2^{-1}(\hat{z})$, an observer of (2) is obtained

$$\begin{array}{rcl} \dot{\hat{x}} & = & f(\hat{x}) + g(h)\Gamma + M(y, \hat{x}, t) \quad \hat{x}^-(t) \notin \hat{\mathcal{S}} \\ \hat{x}^+ & = & \Delta(\hat{x}^-) \quad \hat{x}^- \in \hat{\mathcal{S}} \end{array} \tag{10}$$

with $\hat{\mathcal{S}} = \{\hat{x} \in \hat{\mathcal{X}} \mid \hat{y}_2(\hat{q}) = 0\}$, $\hat{x}^-$ the estimated state prior the impact and $\hat{x}^+$ the updated one.

Remark - Practical point-of-view.
The observer algorithm formally ensures that the estimation errors *exactly* converge to zero. In practice, this property is ensured for a vicinity of zero [2] which the estimation errors are forced to reach and to remain within.
The commutation from the first observer structure to the second one is made through the condition that $T_{SW} := \mathrm{Min}(t)$ such that $t \in [T_I^i, T_I^{i+1}[$ and $\left|\mathrm{Det}\left[\frac{\partial \Phi_1(\hat{x})}{\partial \hat{x}}\right]\right| > D_{SW}$, where $D_{SW} > 0$ a real parameter fixed by the user. The choice of D_{SW} is made in order that the condition number with respect to inversion of $\left[\frac{\partial \Phi_1(\hat{x})}{\partial \hat{x}}\right]$ is not "too much large". ■

IV. Experimental results

Controller design. By supposing the inertia matrix as a diagonal and constant one, the nonlinear control law is based on a PD term[4] and a nonlinear one for compensation of frictions, gravity and centrifugal effects, to track desired trajectories defined as follows, during the single support. It is inspired from [18] and reads as $\Gamma = [\Gamma_{31}\ \Gamma_{32}\ \Gamma_{41}\ \Gamma_{42}]^T$ with ($i \in \{3, 4\}$, $j \in \{1, 2\}$)

$$\begin{array}{l} \Gamma_{ij} = K_{p_{ij}}(q_{d_{ij}} - q_{ij}) + K_{v_{ij}}(\dot{q}_{d_{ij}} - \dot{q}_{ij}) \\ \quad + \mu\dot{q}_{ij} + F\mathrm{sign}(q_{d_{ij}} - q_{ij}) + G_{ij} + H_{ij} \end{array} \tag{11}$$

with G_{ij} and H_{ij} derived from (1) such that

$$\begin{array}{rcl} G(q) & = & \left[\ G_{31}\ G_{32}\ G_{41}\ G_{42}\ G_1\ \right]^T \\ H(q, \dot{q}) & = & \left[\ H_{31}\ H_{32}\ H_{41}\ H_{42}\ H_1\ \right]^T. \end{array}$$

Controller parameters have been tuned as

$$\begin{array}{l} K_{p_{31}} = K_{p_{32}} = 1500, K_{p_{41}} = K_{p_{42}} = 1300, \\ K_{v_{31}} = K_{v_{32}} = 15, K_{v_{41}} = K_{v_{42}} = 15, \\ \mu = 10, F = 5. \end{array}$$

Reference trajectory for single support. The reference trajectory ~~in single support~~ is defined by a parametric optimization [4]. The joints evolution is described by function $q(\theta)$; θ is the angle given in Figure 1-right [15], [1], [6].
Experimental results. A walking gait of several steps has been made. Only actuated joint positions and torques are provided to observer (10). The control law (11) allows a stable walking gait as described by articular positions displayed in Figure 3 for $t \in [28\,\mathrm{sec}, 40\,\mathrm{sec}]$. Note that the steps are not symmetric with respect to their durations, because *Rabbit* is walking on a circle, the inner leg taking less time to follow the trajectories than the outer leg. Observer results are displayed on 2 steps in order to

[4]The controller has been designed only for the observer evaluation and no analysis of closed-loop system stability has been made.

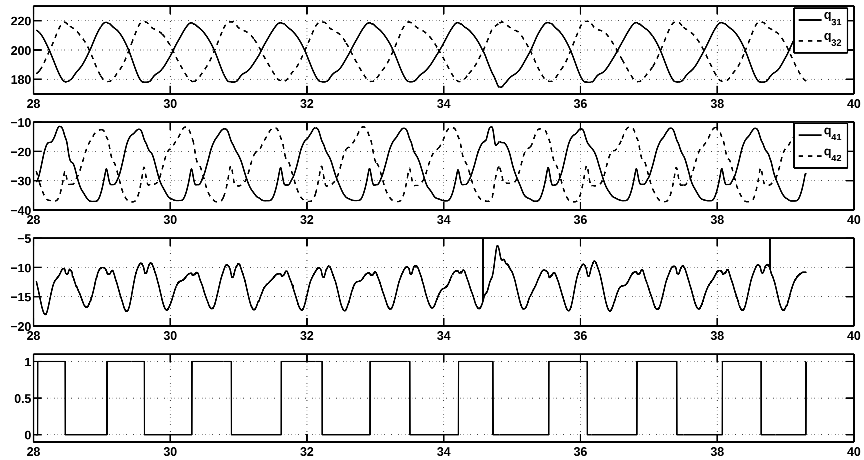


Fig. 3. **From Top to Bottom.** q_{31} and q_{32} (deg) versus time (sec). q_{41} and q_{42} (deg) versus time (sec). q_1 (deg) versus time (sec). Boolean variable ($= 0$ when left stance leg, $= 1$ when right stance leg) versus time (sec).

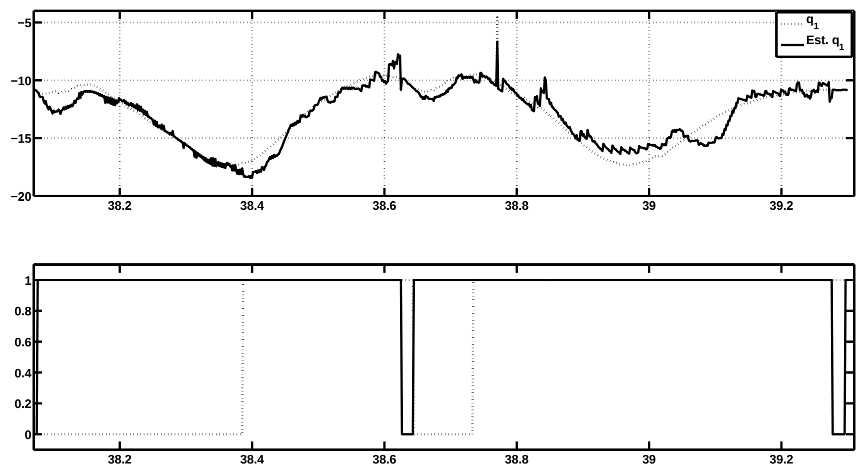


Fig. 4. **Top.** q_1 (deg) (dotted line) and $\hat{q}_1$ (deg) versus time (sec) over 2 steps. **Bottom.** Boolean variables describing the situation of the biped and the used observer structure versus time (sec). *Solid line*: the boolean variable equals 1 in single support, and 0 in double support. *Dotted line*: the boolean variable equals 1 when observer structure is based on observability indices vector $[k_1\ k_2\ k_3\ k_4]^T = [3\ 2\ 2\ 3]^T$, whereas it equals 0 when observer structure is based on observability indices vector $[k_1\ k_2\ k_3\ k_4]^T = [3\ 3\ 2\ 2]^T$.

show that, even if there is the impact, the observer can converge again to the real value of posture angle. The switching conditions between both observation structures have been tuned to get the best results. During the experimentation, it is appeared that estimation accuracy is highly linked to the choice of the commutation. This commutation is made with respect to condition number of matrix $\left[\frac{\partial \Phi_1}{\partial \hat{x}}\right]$. Note that the parameter D_{SW} has to be tuned by a different manner for inner and outer legs: this fact is certainly due to the fact that *Rabbit* is walking along a circle, the observability feature depending on articular positions and velocities.

Two kinds of tests have been made: the first one, named "nominal case", takes the "real" value of torso mass in the observer where as, in the second case

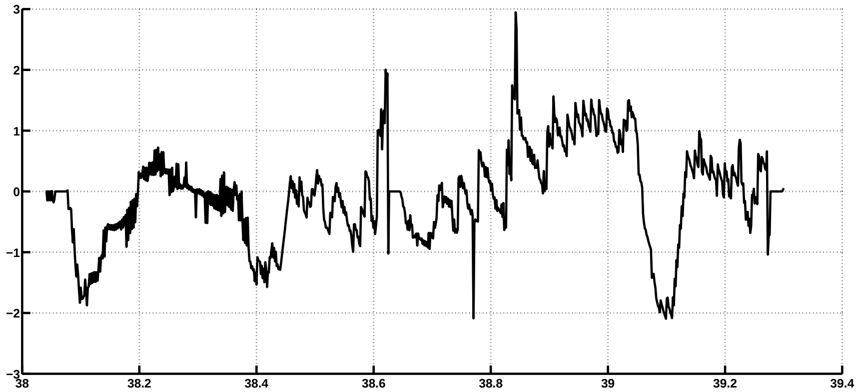


Fig. 5. **Nominal case.** Estimation error of posture q_1 (deg) versus time (sec.) over 2 steps.

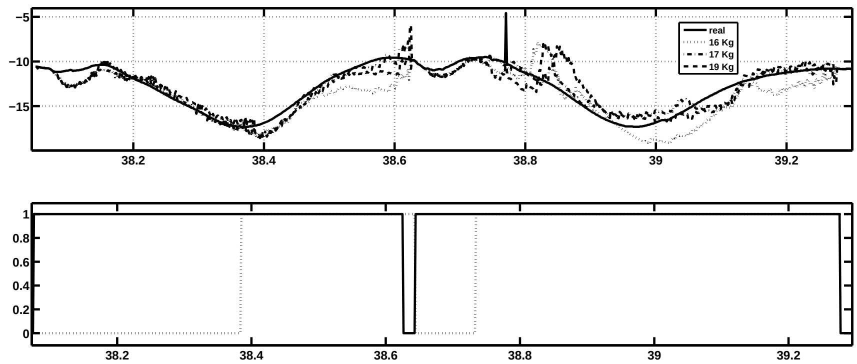


Fig. 6. **Uncertain case. Top.** q_1 (deg) (solid line) and $\hat{q}_1$ (deg) for several values of torso mass (data provided to the observer whereas real torso mass equals 17 kg) versus time (sec) over 2 steps. **Bottom.** Boolean variables describing the situation of the biped and the used observer structure versus time (sec). In *solid line*, the boolean variable equals 1 in single support, and 0 in double support.

named "uncertain case", the observer has a "bad" information on the torso mass given that mass is supposed to be 16 kg or 19 kg whereas it does not change in reality. This second test is considered to evaluate the observer robustness. Note that, even for the "nominal" case, the observer has to be robust given the hypotheses used for the model (rigid impact, no double support, uncertainties due to parameters identification, ...).

Figures 4-5 display the orientation estimation error over two steps once the stable walking is established in the nominal case: the estimation error is quite small (less than 3 deg over two steps). The estimation errors are forced to reduced values; these results prove the practical feasibility of the proposed solution. There is a switching sequence between both observers. Furthermore, there is a double-support which is not taken into account in the synthesis of the observer~~, but it is~~ used to re-initialized the observer to the real state value given that, in this phase, posture is derivable from the articular positions which allows an observer reinitialization. Figure 6 displays the experimental results in case of error on torso mass which does not strongly damage the estimation accuracy. The observer is robust with respect to mass variation. Furthermore, the both tests have shown that the observer is robust with respect to model hypotheses as rigid impact, no elasticity, no slipping, no friction.

V. Conclusion

The main contribution of this paper is the experimental evaluation of finite-time convergence observer for biped robot posture. This observer is based on second-order sliding approach, which ensures robustness with respect to model uncertainties and perturbations. Experimental results show the feasibility of this approach, which provides a better accuracy than previous attempts. An extension of this work consists in estimating the orientation of humanoid robot in 3D when the ankles torques are dramatically limited.

REFERENCES

[1] Y. Aoustin and A.M. Formal'sky. Control design for a biped: reference trajectory based on driven angles as functions of the undriven angle. *International Journal of Computer and Systems Sciences*, 42(4):159–176, 2003.

[2] T. Boukhobza and J.P. Barbot. High order sliding modes observer. In *Proc. IEEE Conf. on Decision and Control CDC*, pages 1912–1917, Tampa, Florida, USA, 1998.

[3] C. Chevallereau, G. Abba, Y. Aoustin, F. Plestan, E.R. Westervelt, C. Canudas de Wit, and J.W. Grizzle. Rabbit: a testbed for advanced control theory. *IEEE Control Systems Magazine*, 23(5):57–79, 2003.

[4] D. Djoudi, C. Chevallereau, and Y. Aoustin. Optimal reference motions for walking of a biped robot. In *Proc. IEEE Int. Conf. on Robotics and Automation ICRA*, pages 2014–2019, Barcelona, Spain, 2005.

[5] L. Fridman and A. Levant. Higher order sliding modes. In *Sliding Mode Control in Engineering, Control Engineering Series*, pages 53–103, Eds. W. Perruquetti and J.P. Barbot, Mark Dekker, New-York, USA, 2002.

[6] J.W. Grizzle, G. Abba, and F. Plestan. Asymptotically stable walking for biped robots : analysis via systems with impulse effects. *IEEE Transactions on Automatic Control*, 46(1):51–64, 2001.

[7] J.W Grizzle, J.H. Choi, H. Hammouri, and B. Morris. On observer-based feedback stabilization of periodic orbits in bipedal locomotion. In *Proc. Methods and Models in Automation and Robotics, MMAR 2007*, Szczecin, Poland, 2007.

[8] A.J. Krener and W. Respondek. Nonlinear observers with linearizable error dynamics. *SIAM J. Contr. Optim.*, 2:197–216, 1985.

[9] V. Lebastard, Y. Aoustin, and F. Plestan. Absolute orientation estimation for observer-based control of a five-link walking biped robot. In *Robot Motion and Control: Recent Developments, Lecture Notes in Control and Information Sciences*, volume 335, pages 181–199, Springer-Verlag, Berlin, Germany, 2006.

[10] V. Lebastard, Y. Aoustin, and F. Plestan. Observer-based control of a walking biped robot without orientation measurement. *Robotica*, 24(3):385–400, 2006.

[11] V. Lebastard, Y. Aoustin, F. Plestan, and L. Fridman. An alternative to the measurement of five-links biped robot absolute orientation: estimation based on high order sliding mode. In *Modern Sliding Mode Control Theory. New Perspectives and Applications - Lecture Notes in Control and Information Sciences*, volume 375, pages 363–380, Springer-Verlag, Berlin, Germany, 2008.

[12] A. Levant. Sliding order and sliding accuracy in sliding mode control. *International Journal of Control*, 58(6):1247–1263, 1993.

[13] P.-C. Lin, H. Komsuoglu, and D.E. Koditschek. A leg configuration measurement system for full-body pose estimates in a hexapod robot. *IEEE Trans. Robotics*, 21(3):411–422, 2005.

[14] P. Micheau, M.A. Roux, and P. Bourassa. Self-tuned trajectory control of a biped walking robot. In *Proc. Int. Conf. on Climbing and Walking Robot CLAWAR*, pages 527–534, Catania, Italy, 2003.

[15] S. Miossec and Y. Aoustin. A simplified stability study for a biped walk with underactuated and overactuated phases. *International Journal of Robotics Research*, 24(6):537–551, June 2005.

[16] C.H. Moog, F. Plestan, G. Conte, and A.M. Perdon. On canonical forms of nonlinear systems. In *Proc. European Control Conference ECC'93*, Groningen, The Netherlands, 1993.

[17] F. Plestan, J.W. Grizzle, E.R. Westervelt, and G. Abba. Stable walking of a 7-dof biped robot. *IEEE Transactions on Robotics and Automation*, 19(4):653–668, 2003.

[18] E.R. Westervelt, G. Buche, and J.W. Grizzle. Experimental validation of a framework for the design of controllers that induce stable walking in planar bipeds. *The International Journal of Robotics Research*, 24(6):559–582, 2004.

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