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Development and control of a one-wheel telescopic active cane

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Abstract— **Population ageing calls for innovative solutions to increase daily living autonomy. Since people autonomy relies on their mobility capabilities, several robotized walking aids i.e. walkers and canes, mainly including navigation functions, have been developed. The existing robotized canes generally consist in statically stable mobile platforms equipped with a rod and a handle. This design alters the basic characteristics of original canes i.e. their weight-lightness and compactness. In this paper, a one-wheel telescopic active cane closer to the original cane concept is presented. Its control law and synchronization with the walking cycle is also given along with experimental results.**

I. Introduction

Population ageing calls for the development of new technologies to help enhancing the elderly's quality of life. The main challenge consists in increasing people's autonomy in their daily-life activities. A first step towards increasing autonomy consists in improving the elderly's mobility so they recover the ability to interact with their environment. Among mobility aids, walkers and canes are generally preferred to wheelchairs when their use is still compatible with the subject's health condition. Indeed walking helps the elderly maintaining a correct postural equilibrium and a good health condition [5].

In this context, several robotized walkers [3], [4], [8], [11] and canes [12], [14], [15] have been developed. Their main goal is to provide more assistance and user friendliness than conventional aids. The last point is critical since it has been shown that using assistive devices increases attention demand among the elderly [16] threatening their postural stability. To meet these objectives, robotized aids are controlled using different strategies. Some are programmed to adapt their behavior with respect to the subject's intention or help tracking a predefined trajectory, while others are intended to secure people's postural stability. Robotized assistants are currently composed of conventional assistants like devices mounted on statically stable mobile robots *i.e.* platforms with at least three wheels. While this design approach does not considerably increase the size of robotized walkers when compared to conventional ones, it alters the main characteristics of canes. Indeed, the included mobile platforms have larger support platforms when compared to the distal tip of conventional canes. This results in devices not looking like canes. The base of support size of robotized canes could not be reduced without increasing falling over risks.

One ongoing project in our laboratory consist in developping a one-wheel telescopic active cane. This design allows to stay closer to conventional canes characteristics. Indeed with one wheel, it is easier to design a thin and compact cane reducing the support surface to the only contact between the wheel and the floor. In this paper the current prototype design is presented. The issue of synchronizing the active cane with a straightforward gait is tackled as well.

The sequel of the paper is organized as following. In section II, the developed cane is described. In section III a conventional cane assisted walking is analyzed in order to derive the control strategy for the developed active cane. This strategy is given in section IV. Experimental results are then presented in section V. Conclusions and future works are finally discussed.

II. Active Cane Prototype

A one-wheel telescopic active cane prototype weighing 5,7 kg has been developed (Fig.1). In this section, its mechanical architecture, its intended use and its embedded control electronics are described.

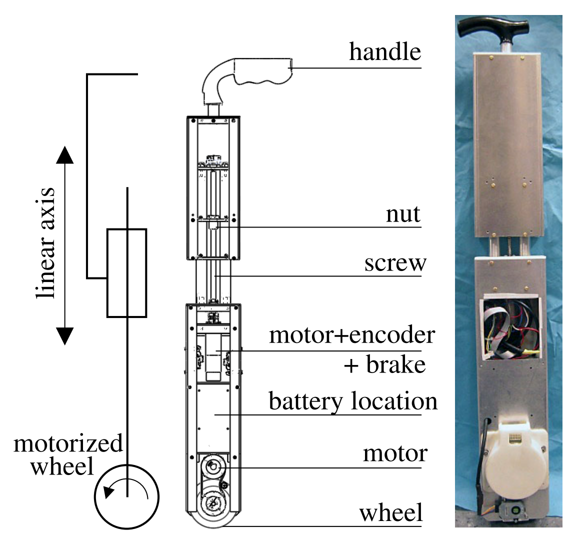

Fig. 1. Cane prototype ((left) a schematic of the cane kinematics (middle) a CAD view (right) the current prototype)

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A. Mechanical architecture

The robotized cane is composed of a linear actuated axis and a motorized wheel (Fig.1). The linear axis is actuated using a Maxon EC-Max 30 brushless motor. The rotary to linear motion conversion is ensured through a ball screw mechanism. The linear axis displacement range is of 0.15 m admitting a cane length variation from 0.8 m to 0.95 m. Its nominal velocity and force are respectively $0.33\,\mathrm{m.s^{-1}}$ and $150\,\mathrm{N}$. A failsafe brake is equipping this axis to maintain a constant length when the power is off. The wheel is actuated using a belt-pulleys mechanism powered by an EC-flat motor equipped with a Maxon GP52-12 gear. The wheel nominal velocity and torque are respectively $23\,\mathrm{rad.s^{-1}}$ and 4.6 N.m. Both motors are equipped with incremental optical encoders. As the wheel diameter is equal to 0.1 m, the nominal cane linear tip velocity and tangential force are respectively $1.1\,\mathrm{m.s^{-1}}$ and 92 N.

B. Intended use

The developed active cane is intended to be held like a conventional cane. The motorized rod and wheel allow the cane to move without applying forces on the subject's hand. Unlike conventional canes, the proposed active device is not expected to be lifted and put on the floor at each stride. Instead, it should track the subject's forward gait and stop moving to provide mechanical support when necessary. The gait tracking is achieved by the means of a wireless sensor equipping the subject. When the subject takes a turn, he/she just has to rotate the active cane along its axis and continue walking.

C. Control electronics

The motors actuating the telescopic axis and the wheel are driven using two Solo-Whistle servo drives set in velocity control mode. The reference velocities are sent to the servo drives using a mbed LPC1768 micro controller through a CAN bus. Reference velocities are computed based on the measurements of the cane state and on two Inertial Measurement Unit (IMU) signals. One IMU is attached to the cane while the second is equipping the cane user. The two IMUs are connected to an Arduino Due board using respectively a serial and bluetooth communication protocols. The Arduino board sends the acquired data to the mbed LPC1768 through a serial bus. The two servo drives, the mbed and the arduino board are powered using two LiPo batteries. Figure 2 illustrates the cane electronic wiring diagram.

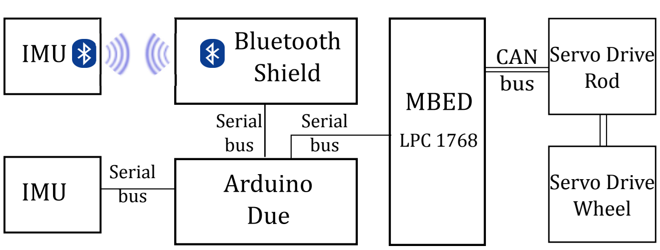

Fig. 2. Cane electronic wiring diagram

III. Conventional Cane Assisted-Walking

In this section, an analysis of straightforward conventional passive cane assisted gait is given. This analysis is achieved to determine the strategy for synchronizing the active cane motion with the gait cycle during forward walking. First, the cane assisted gait structure is recalled. Then measurements of both thigh and passive cane angles enables to select a control strategy for the active cane.

A. Cane assisted gait structure

The cyclical properties of human straightforward gait allows considering it as a succession of strides. During a stride, each leg alternates between a stance and a swing phase. The transition between the two phases occurs after a double stance during which both feet touch the floor. When a leg is impaired, a cane may be prescribed to assist the gait. A cane may be used in a controlateral or ipsilateral way. Without loss of generality, a controlateral use of the cane is considered hereafter [13], [17]. In a controlateral use (Fig. 3), the cane is held on the opposite side of the weakest limb enabling a reduced load on both the affected limb and hip [6]. Aside from enhancing the postural stability by increasing the base of support, a cane provides breaking and propulsive forces to support the subject's weakest leg [2], [9]. The breaking and propulsive forces are needed respectively during the heel strike and the push off of the weakest leg.

Figure 3 depicts a cane-assited stride. It begins with the push-off performed by the weak leg assisted by the cane (a). Then, the weak leg and the cane swing together while the other leg remains in contact with the floor (b). The cane supports the weak leg during the heel strike (c). The sound leg swings, while the weak leg foot and the cane tip remain motionless (d), until the end of the cycle (e).

B. Cane assisted gait analysis

The previous description of the assisted gait structure shows a strong correlation between the passive cane and the weak leg displacements. Following that, experimental results confirming this observation are given.

1) Experimental Setup: Four healthy subjects equipped with a knee brace and a modified sole have participated to the experiments. The equipment is intended to simulate walking troubles [1]. They were first asked to walk during five minutes to get used to the experimental conditions.

Secondly, the subjects were asked to walk with the help of a passive cane during 5 minutes. A CodaMotion system composed of three infrared cameras has been used to capture their motion. To this purpose, both subjects limbs and cane have been equipped with active infrared markers (see Fig. 4).

2) Results: The thigh and cane orientations in the sagittal plane have been computed using the markers positions captured during the cane assisted walking. These angles for the four subjects during a straightforward gait are plotted in Fig. 5. The plots show a good superimposition between the two angles. A synchrony and an almost similar range are observed between the orientation of the cane and the weak

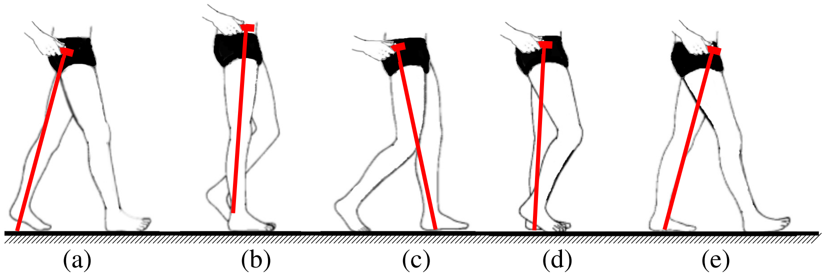

Fig. 3. Cane assisted stride

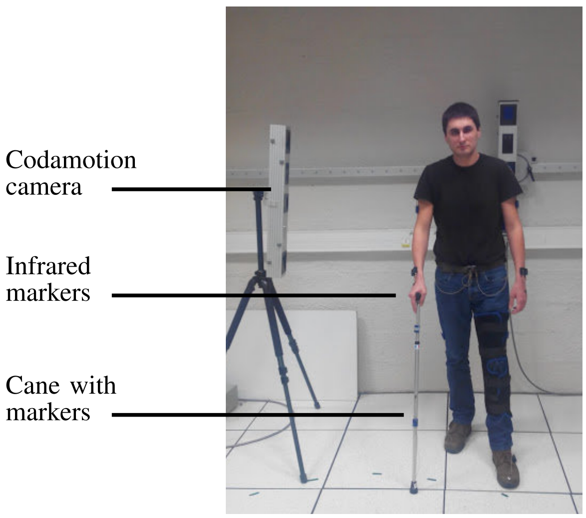

Fig. 4. Motion capture markers positions on the subjects and the cane

leg thigh during the cane assisted walk. This correlation will be used in the next section to elaborate a control strategy for the active cane.

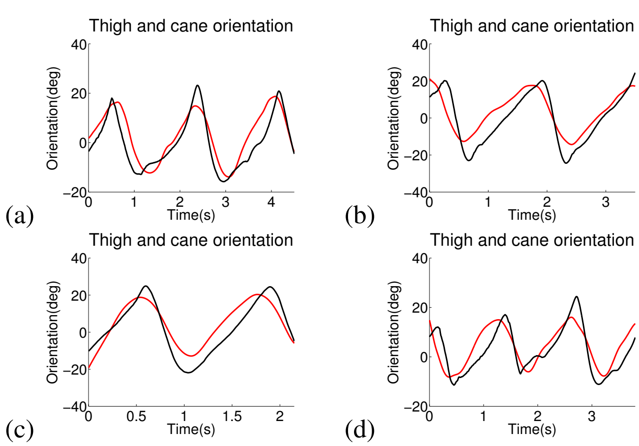

Fig. 5. Comparison between cane (black line) and impaired leg thigh (red line) orientation during cane assisted walking

IV. Control scheme

In the following section, the strategy adopted to synchronize the cane motion and the straightforward gait is first described. The active cane modeling and the control law are then presented.

A. Strategy

Given the results obtained in the last section, we propose to control the cane orientation to track the weakest leg angle. This allows to assist this leg when necessary. To this aim, an IMU providing the angle that should be tracked by the active cane is strapped to the subject's thigh (see Fig. 11).

Using this strategy leads to the active cane behavior depicted in Fig. 6. The cane actively tracks the orientation of the weak leg during its swing phase. During the double stance phase, the active cane does not move since the thigh angle does not vary significantly. At the beginning of the sound leg swing phase, the angles of the cane and the weak leg's thigh are equal. During the remainder of this phase, as the subject's hand is moving forward with the trunk, the cane orientation and the thigh's angle vary in the same way. This results in a motionless cane tip and rod. Again during the double stance phase, the cane remains at rest until the beginning of the weak leg swing.
Note that this strategy is in accordance with [7] where the authors take advantage of the synergy between the cane and the legs motion to control a HAL Exoskeleton.

B. Modeling and control law

In this subsection the thigh angle tracking control scheme is described. Before giving the control law, the differential kinematic model of the active cane is first derived. This model gives the relationship between the cane angular velocity $\dot{\theta}$ and the generalized velocities $\dot{d}$ and $\dot{l}$ (Fig. 7). $\dot{d}$ and $\dot{l}$ denote the velocities of respectively the cane tip and the telescopic linear axis.

The cane orientation θ, d and l are related as follows:

$$\sin\theta = \frac{d}{l} \tag{1}$$

Differentiating this equation gives:

$$\dot{\theta} = \frac{1}{l\cos(\theta)}\dot{d} - \frac{d}{l^2\cos(\theta)}\dot{l} \tag{2}$$

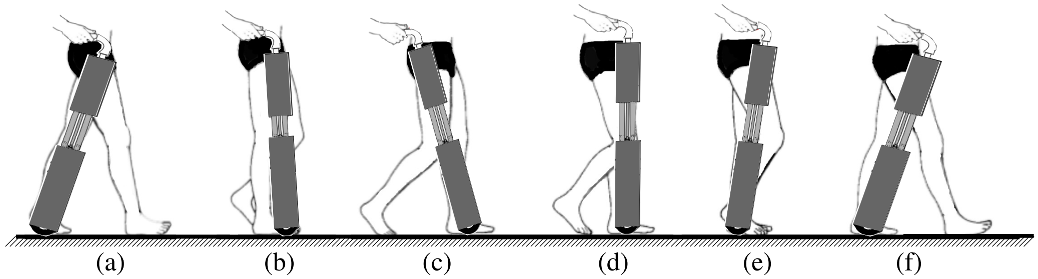

Fig. 6. Active Cane assisted stride

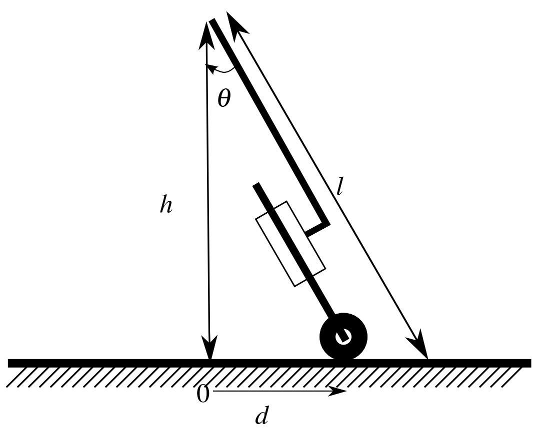

Fig. 7. Cane model, l length of the cane, h height of the handle, d handle-wheel floor distance

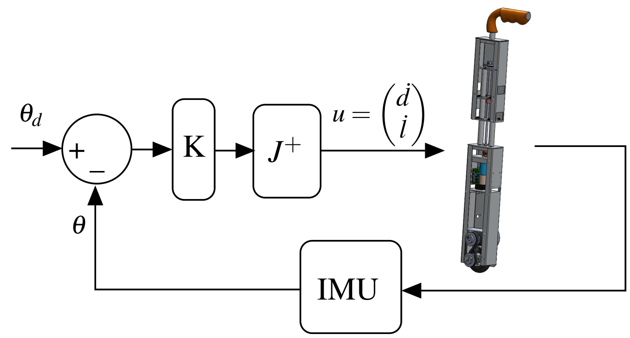

Fig. 8. Cane control scheme

This equation can be rewritten as:

$$\dot{\theta} = \mathbf{J} \begin{bmatrix} \dot{d} \\ \dot{l} \end{bmatrix} \tag{3}$$

where : $\mathbf{J} = \begin{bmatrix} \frac{1}{l\cos(\theta)} & -\frac{d}{l^2\cos(\theta)} \end{bmatrix}$ is the Jacobian matrix of the active cane.

Since $\frac{d}{l} = \sin(\theta)$, the Jacobian matrix has been rewritten as following:

$$\mathbf{J} = \begin{bmatrix} \frac{1}{l\cos(\theta)} & \frac{-\tan(\theta)}{l} \end{bmatrix} \tag{4}$$

This way, the Jacobian will not depend on d and thus on the motorized wheel encoder information. This avoids odometry errors that arise during long distance motion [10].

To follow the subject's gait, the cane orientation should be servoed to the impaired leg's one denoted θ_d. As depicted in Fig. 8, the control law writes:

$$\begin{bmatrix} \dot{d} \\ \dot{l} \end{bmatrix} = K \underbrace{\begin{bmatrix} \frac{l cos\theta}{1+sin^2\theta} \\ \\ \frac{-l sin\theta cos\theta}{1+sin^2\theta} \end{bmatrix}}_{\mathbf{J}^+} (\theta_d - \theta) \tag{5}$$

where :

- K is a proportional control gain.
- $\mathbf{J}^+$ is the pseudoinverse of the Jacobian matrix $\mathbf{J}$.

$\dot{l}$ and $\frac{\dot{d}}{r}$ are sent as reference velocities to the motors drivers (where r is the wheel radius). The velocity servoing loop is considered instantaneous since it is much faster than the cane orientation control loop.

V. Results

Before describing the synchronization of the active cane motion with a straightforward gait, the basic feedback control properties of the implemented control law are given.

A. *Preliminary experiments*

According to the experiments presented in section III, the cane orientation range is $[-25°, 25°]$. To achieve an experimental evaluation of the active cane control law, an orientation reference trajectory composed of $-30°$ and $30°$ magnitude steps is considered. During this experiment, the cane handle is kept at a stationary position by a subject.
Figure 9 shows the cane response to the above described reference trajectory. The rod and the cane tip velocities are also given. The obtained tracking performances are satisfying with an almost unit gain and an about 0.4 second rise time. The cane orientation response to the first $-30°$ magnitude step is achieved by a backward displacement of the tip (negative speed) and an extension of the telescopic rod (positive speed). As for the second reference change (from $-30°$ to $30°$), the cane tip moves forward. The rod

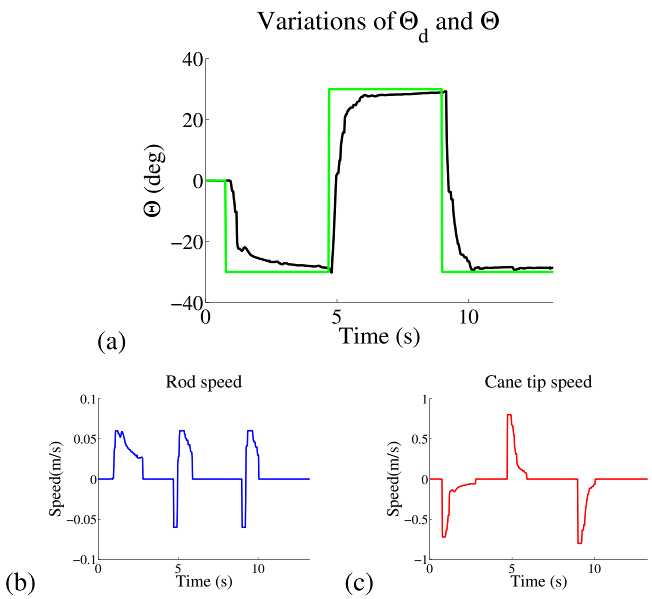

Fig. 9. Cane response to a reference orientation trajectory composed of $-30°$, $30°$ and $-30°$ steps. θ_d in green and θ in black

shortens until the cane is vertical and then extends.

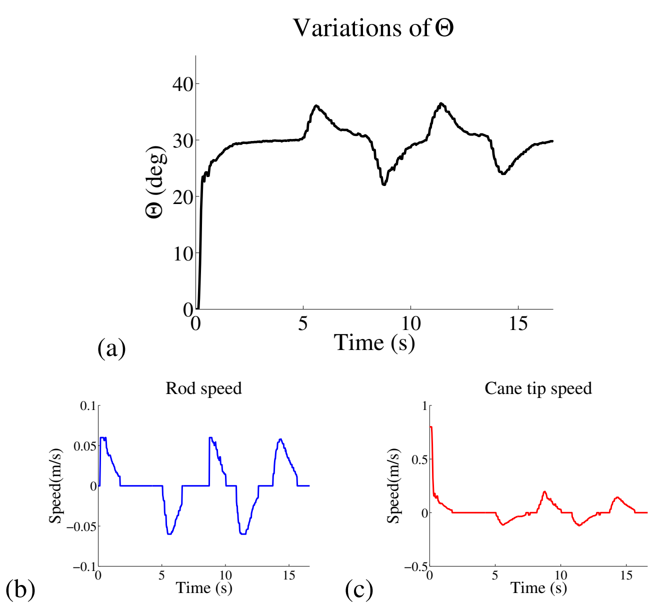

Fig. 10. Disturbance rejection experiment for a reference orientation of $30°$.

A second experiment has been conducted. In this experiment, the cane reference orientation is set to 30 degrees. The subject holding the cane handle is asked to change his hand position to induce four disturbances. The active cane is supposed to move in order to keep its desired orientation.

The behavior of the cane during this experiment is shown in Fig. 10. One can see that when a disturbance occurs due to the subject's hand motion, the cane actively recovers its desired orientation as expected.

B. Synchronization with the gait cycle

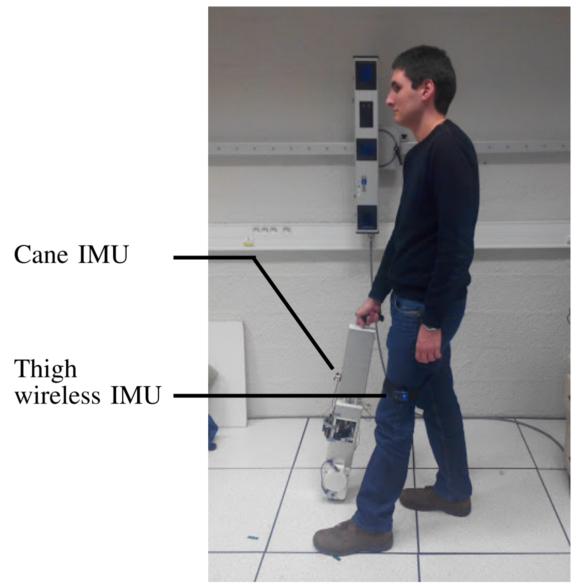

Fig. 11. A subject equipped with a wireless IMU on his thigh and holding the active cane

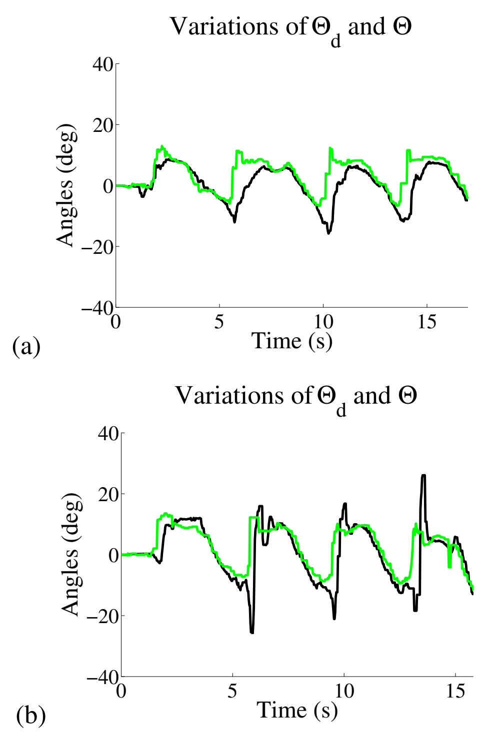

Fig. 12. Cane following experiments, θ_d in green, θ in black

In the following, the results obtained using the strategy described in section IV are given and discussed. A wireless IMU is attached to the subject's thigh (Fig. 11) . The experiment begins with the subject standing still and keeping his feet parallel. The cane is held vertically. The

subject is then asked to begin walking by swinging first the leg equipped with the IMU.
Figure 12 shows the results of two walking experiments with two different stride lengths of almost 0.87 m (Fig. 12 a) and 0.96m (Fig. 12 b) . The cane has achieved a quite good tracking of the weak leg angle with respectively a RMSE of 6° and 7°.

The cane behavior during one stride is given in Fig. 13. The active cane begins by tracking the orientation of the weak leg during its swing phase (Fig. 6 a-c). From the weak leg heel-strike until the end of its stance phase, the cane rod and tip are motionless (Fig. 6 c-f), allowing the subject to use it like a passive conventional cane. Forces can thus be applied safely on the cane. This behavior is explained by the subject's hand motion resulting in a rotation of the cane which equal to the thigh angle rotation. For more safety, the rod and tip velocities may be set to zero at the beginning of the double support phase detected by the IMU attached to the subject's thigh.

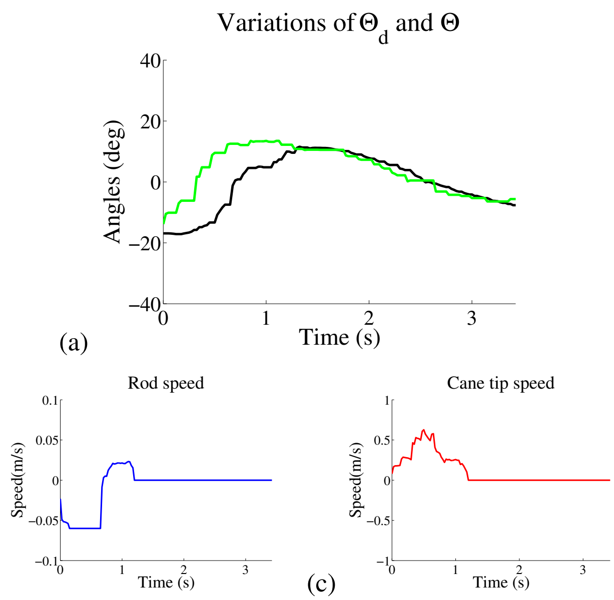

Fig. 13. Cane behavior during a stride, (a) θ_d in green, θ in black

VI. CONCLUSIONS

In this paper, the development of a one-wheel telescopic active cane has been introduced. This cane keeps the main characteristics of a conventional cane, namely its compactness and reduced tip size. The synchronization of the active cane motion with a straightforward gait has also been achieved. To this purpose the cane orientation has been servoed to the angle of the weakest leg thigh. Promising experimental results have been obtained.
Future work includes two main topics. The first one consists in the assessment of the active cane benefits. To this aim, a comparison of the forces applied on the active cane have to be measured and compared to those obtained using a conventional cane. Besides, the use easiness has to be investigated, through experiments involving subjects with gait impairments. For that purpose, the safety of the cane will be enhanced to cope with gait pattern disruption or falls. The second topic is related to control issues. Indeed, in the present work, only straightforward walking is considered. The cane control should handle other situations e.g. when the walking direction changes or the more challenging stairs climbing.

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