Sensor-Based Estimation of Human Motion for Control Synchronization

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***Abstract*—This paper addresses the question of embedded human motion sensing, in the framework of interaction with an artificial controller, either for activating a robot or for stimulating impaired human links. After a short presentation of the sensing problem and of the related measurement technologies, we describe the two main applications we have considered. The first one is the early detection of the paraplegic's intention in a Sit-to-Stand Transfer problem; here the actuation consists of the electro-stimulation of the knee extensors of the patient. The second is the estimation in real time of a variable allowing to synchronize the motion on a robot leg or of the impaired leg of a stroke patient on a human stationary walking gait. A few perspectives are drawn in the conclusion.**

I. Introduction

THIS paper addresses some aspects of the sensing problem in human-robot interaction. Since it takes place in a special session dedicated to Philippe Coiffet, it will not be organized in a classical way. Indeed, we will not start with the usual state of the art:the bibliography related to the questions specifically considered here can be found in the references [1] [2] [3] [4].These papers give also technical details concerning the work which will be presented in the following, and we will therefore not conduct the related formal developments. Instead, we will try to rise the general questions associated with sensing in human-robot interaction, mainly when control issues are concerned. We will illustrate that point of view through two examples of works we have recently completed.

II. Sensing for motion-based interaction

A. Generalities

When considering interaction between a human and an intelligent and active artificial system, like a robot, there necessarily arises the problem of controlling the system in order to optimize this interaction. The optimization criteria are linked to the nature of the task. However, in all cases, the control needs to be fed with information coming from the human and the system, in order to achieve at each time the best kind of interaction, and this can be done through adequate sensors. In this paper, we will focus on a particular case of interaction, which is exclusively done through body and/or link motions.Modalities with a high level of cognitive involvement, like emotion, vision, voice are therefore excluded. The most classical example of such low-level interaction is the master-slave teleoperation, pioneered by Philippe Coiffet (see [5] for example). Here, the interaction is of kinesthetic type, and the required sensing is basically the one of interaction forces. When the master-slave system is computer-aided, these forces may be either directly sensed or synthetized, for example on the basis of safety distance measurements.

Another wellknown example of sensing for motion-based interaction can be found in the area of virtual reality,which is also a Philippe's contribution domain (see [6]). Datagloves measuring hand and fingers positions, and external motion capture systems based on multiple cameras or detectors and, generally, passive or active markers, are the most largely used sensing systems. The provided data can be used in a pure virtual framework or to control a robot, either in real time or as an off-line trajectory generator.

The applications of human motion sensing for the control of artificial devices of systems are numerous. We can cite:

- teloperation of a robot by motion mimicking, through a control unit which ensures the functions needed for online adaptation, like safety, scaling, etc...*Examples: bilateral teleoperation, piloting of a humanoid, surgical robotics*;
- starting of tasks of a robot or an automatic device on the basis of recognized human motions. *Example: control of an assistance robot by a disabled in a wheelchair*;
- control of an exoskeleton. *Examples: walking assistance for disabled, augmented soldier* ;
- control of impaired limbs from valid ones.*Example: training of stroke patients through functional electrostimulation (FES).*

Let us finally notice that human motion sensing can also be used in open loop in many cases, for example for analyzing sport performance, building biomechanical models, monitoring the behaviour of elderly or evaluating the improvement due to training in rehabilitation.

B. Sensing technologies

The sensors that are likely to be used for the applications cited above share some general requirements: they have to be wearable and usable in free outdoor space (contrary to motion capture systems); they should be adapted or easily adaptable to the aimed function, in particular to the kind of desired control task ; they have to be “friendly ”: easy to mount (on the skin of the human body or on his clothes, low sensitivity to positioning uncertainties), minimally invasive (small, discreet, wireless, nicely designed...), easy to use by non-experts. Since they are embedded, they should have a low energy consumption, with long range autonomy. They have also to integrate radio components and communication protocols adapted to the architecture (local wireless sensor network): guarantee of safety

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and privacy, bandwith and latences compatible with control requirements, possibility of data synchronization... And all that should be available at a cost as low as possible!
In the last decade, progresses in MEMS design have made available on the market very accurate microsensors, that can be acquired from several commercial providers. Among them, a particular class meets most of the previous requirements: the inertial microsensors (micro IMUs). They consists either of micro accelerometers or of micro gyrometers, or use combination of both. Gyrometers are still presently energy-consuming and are often used only when it is needed to improve the data provided by other sensors. Accelerometers are cheap and accurate, but the basic difficulty is to separate the self-motion component from the gravity one. Another type of interesting microsensor is the magnetometer. Contrary to similar sytems used in motion capture, where the magnetic field is artificially generated, these sensors measure their own orientation with respect to the earth's field, with however prevents from their utilization in highly magnetically disturbed areas. An idea is therefore to combine accelerometers and magnetometers in a redundant way in order to compute the attitude of the sensor accurately. This has be done for example by CEA-LETI in Grenoble France, by combining two three-axis sensors of each type in a single chip (figure 1). A dedicated algorithm allowing the reconstruction of attitude in real-time is integrated in a data processing unit. A smart wireless version, called "Starwatch" has also been realized (see figure 2).

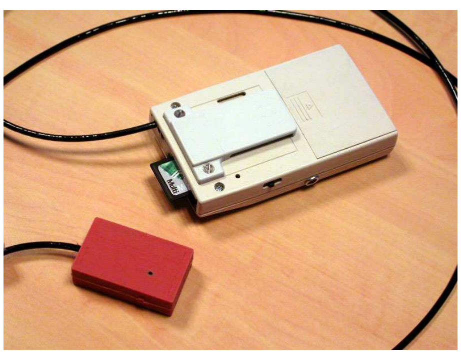

Fig. 1. The CEA-LETI Attitude Sensor with its Data Processing Unit

Fig. 2. The Starwatch System : Wireless Sensor, Radio Station and PC

III. Two examples of application of attitude microsensors in rehabilitation

In this section, we briefly present two pieces of research we have recently conducted. Both of them use the CEA-LETI attitude microsensors previously described. It should be noticed that we are not exactly in the context of human-robot interaction in the most strict sense, since, but in a single case, there is no external robot in the loop. Nevertheless, we can consider that the presented framework is of similar nature: in fact the sensor data are used to activate an electrostimulation system, aimed at moving impaired (therefore passive) legs of disabled, therefore acting as a particular case of robotics actuator.Indeed, the interaction paradigm here is specific of the rehabilitation domain, i.e. : how to use the motion of valid limbs in order to control the one of artificially actuated links?

A. *A Sit-to-Stand application*

We consider here the Sit-to-Stand transfer (STST) problem, for paraplegic patients who are assisted by FES. This application is of great interest in rehabilitation, since such a movement is often repeated in a day, and is a usually a preliminary stage to gait initialization. The stimulated muscles are knee extensors. An important issue in that case is to perform an overall optimization of the energy which is required to achieve the STST, in order to avoid overstimulation of knee extensors and excessive force application in the upper limbs, and, finally,to minimize the muscular fatigue of the patient. This requires to detect as early as possible the intention of standing, and to synchronize the voluntary motion of the patient (trunk and upper limb) with the stimulation of lower limbs. It has been shown that the trunk initiated the STST in all cases, which is also visible through the associated APA. Moreover, experimentations conducted on several subjects have shown that trunk orientation and acceleration patterns presented low intra and inter-variability and were highly reproductible in term of time sequencing. Therefore, this motion, which occurs soon enough before the active STST stage, is a good candidate to the early detection of the patient's STST intention, through an adequate sensor.
The sensor used in this application was the one from CEA-LETI described in the previous section.It was mounted in the back of the trunk, at the C7 level (see figure 3). The quality of measured Z acceleration (see figure 4) was good enough to decide to use this single measurement to characterize the beginning of STST. In order to minimize the detection delay while avoiding to get too many false alarms, two statistical methods were used: one based on the monitoring of a correlation coefficient, the other on the sequential detection of abrupt changes. Both of them give good results (sensitivity: 96.7 %, selectivity w.r.to other motions: 76,2 %). Moreover, the detection time takes place in an interval of 100 ms from the true STST beginning (measured in an independent way), which is low compared to the total STST duration (up to 2 sec). Finally, thanks to the microsensor associated with an adequate signal procesing, an accurate synchronization of the FES with regard to the patient's intention in order to minimize his fatigue has been shown to be possible

Fig. 3. Sensor Frame

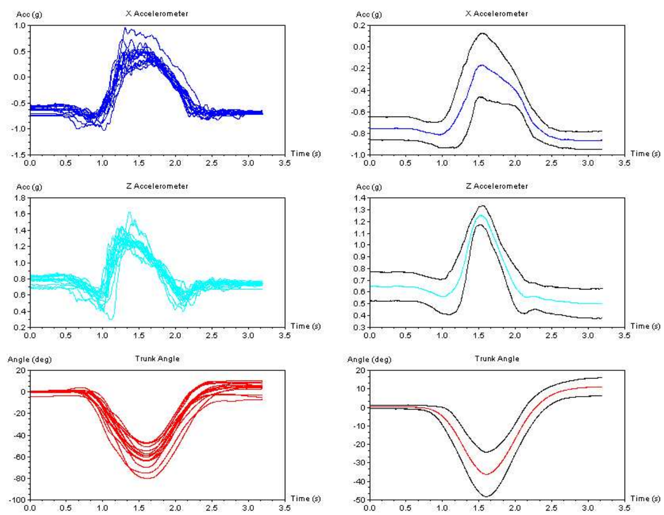

Fig. 4. Left column: X acceleration, Z acceleration and trunk angle, for 15 experiments with a single subject during STST. Right column:average values and standard deviations for 67 experiments with 4 subjects

B. On-line generation of a sensor-based synchronization signal

In the previous section, the sensor signal was used as a kind of optimal trigger for a temporally fixed FES sequence. We will now present a case where the sensed motion is used in continuous time in order to pilot the controller of an external actuator. In this application, the considered movement is a walking one, resulting from a steady-state human gait. This gait is observed by, again, a CEA-LETI attitude microsensor, i.e. a *Starwatch* mounted on the thigh (see figure 6). Assuming that the motion takes place approximately along a straight direction, only the estimated angle between the thigh and the vertical is used in the following. The objective is therefore to use such a sensor output in order to synchronize the motion of another leg w.r.to the one of the observed one. It is assumed that the trajectory of the other device is generated independently, but has a degree of freedom through a temporal scaling parameter. Therefore, the knowledge of a single parameter of the "master" walk, called the "phase" is sufficient for ensuring the synchronization.

As previously, solving this problem requires a dedicated signal processing method, which has to be accurate in the estimation of the phase, robust to uncertainties and disturbances, and adapted to low-cost real-time implementation within an embedded system. The adopted approach can be summarized as follows: firstly, an implicit model of the sensed walking cycle is defined. In practice, a 2nd order non-linear oscillator with limit cycle is generally well-fitted to the cyclic motion of a human leg while walking. From another point of view, this can be seen as an implementation of a CPG (*Central Pattern Generator).* We use therefore a Van der Pol oscillator, modified in order to include the rather strong asymmetry of the cycle. A nonlinear observer is then associated with this theoretical model. By injecting at each time in this observer the output of the attitude sensor, we obtain as output an estimation of the current phase (i.e. the instant "position" along the cycle). Figure 5 gives an example of a phase estimation result, obtained on actual experimental data. In order to improve the accuracy of the algorithm, one may use several sensors instead of one. The previous method can then be extended using an Hopf oscillator in order to design a dynamical filter working on the set of phases independently estimated by each sensor. The method has shown a nice robustness to measurement noise, to uncertainties on the model parameters, and to variations of the frequency of the walking cycle. Two applications of this general method have been considered.

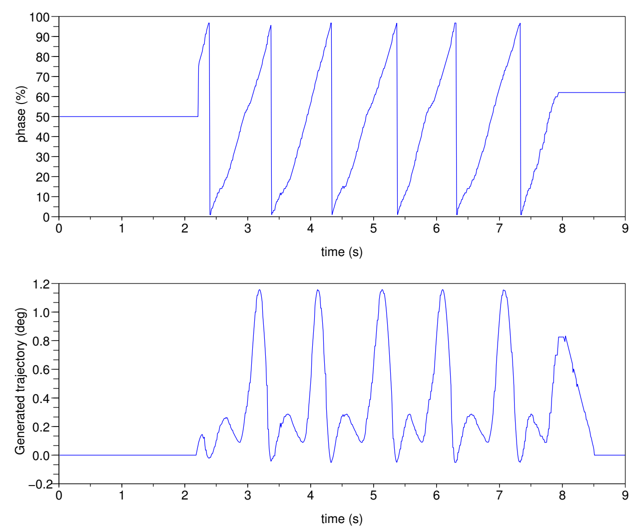

Fig. 5. Top: estimated phase; bottom:generated knee angular trajectory

The first one, illustrated in fig 6, is a kind of teleoperation of a biped robot, the legs of which have anthropomorphic characteristics close to the ones of the "master" walker. Here, the angular trajectory of the knee joint, computed off-line, and PID-controlled, is synchronized on the one of the human (figure 7).

The second application concerns the rehabilitation of the walk for stroke patients. In that case, the motion of the valid leg allows to control through FES the impaired leg, inside a training protocol under the supervision of a clinician. The estimated phase signal can there be used to synchronize the muscular activation patterns specific to the patient, along the walking cycle. An implementation of the system in connection with a commercial stimulator for correcting the *Drop Foot Syndrome* is under progress.

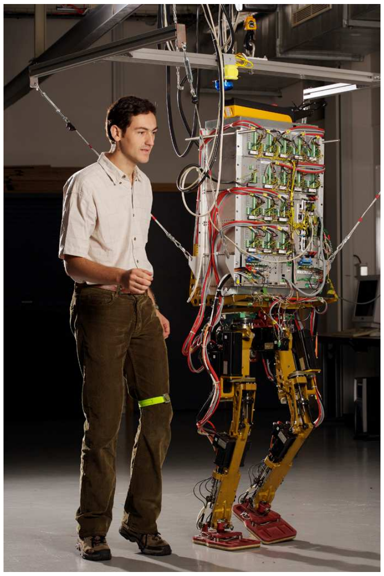

Fig. 6. Teleoperation of a Biped Robot using the Starwatch System

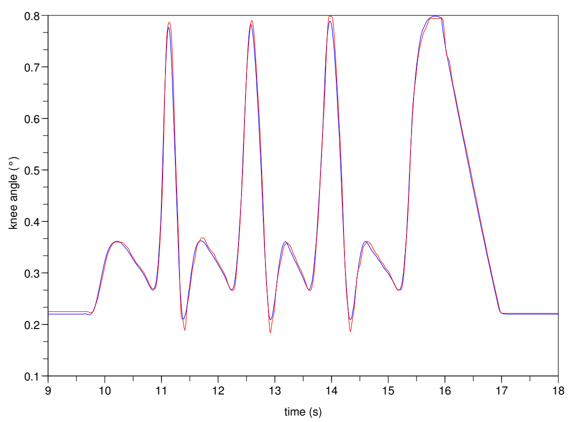

Fig. 7. Trajectory of the robot knee: in blue the desired one, issued from the synchronization algorithm; in red, the obtained trajectory

IV. Conclusion

In this paper, we have presented two examples of research results using microsensors measuring human motion for controlling a stimulation system or a robot actuator. We strongly believe that we are only at the beginning of applications exploiting motion sensors embedded on human body. A first reason is that microsensor technology will certainly still improve, in terms of size, physical principles used in micro or nano sensing devices, energy consumption and integration of computing and communication functions. All these issues will increase the sensor performances and enlarge the field of potential applications. Another point is that a great added value may come from the coupling of other types of measurements to attitude ones: embedded cameras ensuring dedicated functions, like target tracking or visual servoing; soles equipped with pressure sensors; footswitches; proximity or local range sensors; force/torque sensors; GPS devices; physiological sensors (blood pressure, heartbeat, oxygen consumption...). Finally, motion sensors can also improve the human robot-interaction based on a BCI (*Brain-Computer Interface*) approach, by resolving ambiguities or by controlling low-level aspects of interaction, like reflex loops, reducing in that way the cognitive workload.

To conclude, a lesson we can learn from our own results is the importance of the quality of data/signal processing in the success of an application. A good sensor is nothing in itself if it is not associated with efficient algorithms, robust, reliable, adapted to the task and likely to be embedded. As long as the number and the diversity of the sensors will increase, the complexity of the processing will therefore increase, and the failure risk too. This point is all the more important when a controller in relation with a human is involved, since safety questions are then mandatory.

Acknowledgment

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Bernard Espiau received a PhD degree in Automatic Control (Nantes, France, 1975). He conducted several projects in robotics, in the areas of sensor-based control, visual servoing, control architectures, bipedal locomotion. He launched the BIP project, first anthropomorphic biped robot in Europe, completed in 2000. He advised 25 PhD students and authored more than 100 papers and book chapters. He is coauthor of the reference book "Robot Control, the Task-function Approach" (Oxford University Press, 1990). From 1988 to 1992, he was the Head of a postgraduate engineering school in automatic control and computer science in Sophia Antipolis. From 2001 to 2007, he was director of the INRIA Rhône-Alpes Research Centre (450 persons) in Grenoble, France. He is presently Deputy Scientific Director at INRIA.