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A Novel Technology for Motion Capture Using Passive UHF RFID Tags

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***Abstract*—Although there are several existing methods for human motion capture, they all have important limitations and hence there is the need to explore fundamentally new approaches. Here we present a method based on a Radio Frequency IDentification (RFID) system with passive Ultra High Frequency (UHF) tags placed on the body segments whose kinematics is to be captured. Dual polarized antennas are used to estimate the inclination of each tag based on the polarization of the tag responses. The method has been validated experimentally for the shank and thigh in the sagittal plane during treadmill walking. The reference joint angles for the validation were obtained by an optoelectronic system. Although the method is in its initial phase of development, the results of the validation are promising and show that the movement information can be extracted from the RFID response signals.**

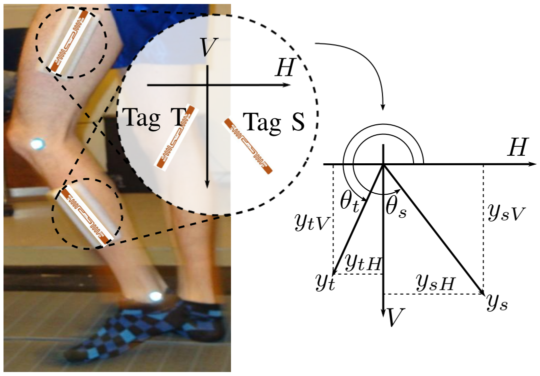


Fig. 1. The placement of tag T and S on the thigh and shank segments respectively, with their inclinations θ_t and θ_s highlighted using a vector notation representing the power, y, in the tag response.The indexes s and t refer to the shank and thigh, and the vertical and horizontal components are respectively denoted V and H.

I. INTRODUCTION

Measurement of human movement is of interest in many fields, such as biomechanics, rehabilitation engineering, motor control, as well as in gaming and movie industries. Human movement is characterized by the kinematic trajectories (i.e., relative and/or absolute angles) of body segments, which can be recorded using several existing technologies [1].

The golden standard for human motion capture is the optoelectronic system with infrared cameras. The cameras track the positions of markers placed on the body segments, and from this information a segment 3D pose (i.e., position and orientation) is obtained. This system has high precision, but the measurement requires expensive laboratory equipment, and thus the analysis is typically confined to a laboratory space. Moreover, the measurement may be influenced by light reflections (i.e., ghost markers) and marker occlusions (i.e., a line of sight problem). Alternative to optoelectronic systems, goniometers can be used to directly measure joint angles. The most common goniometers for motion analysis comprise two plastic bars that are placed on the body segments and a flexible angle sensor element. Contrary to optoelectronic systems, goniometers are suitable for outdoor measurements but are easily breakable, difficult to align with the bodily axis and to place consistently. Inertial sensors measure acceleration (accelerometers) or angular velocity (gyroscopes) [2]. These are practical sensors convenient for daily use since they have low cost and small size. However, computing joint angles from noisy velocity/acceleration signals is undermined by several sources of error (e.g., integration drift, collision accelerations) [1]. Typically, a cluster of sensors has to be used, and the angle is estimated employing sensor fusion methods (e.g., Kalman filtering) to improve robustness. However, this also increases the complexity and cost of the measurement system. Magnetic systems, which use sensors placed on the body to measure the field emitted by a source, are also available, but have not been widely used due to restrictive limitations [1]. Finally, markerless motion tracking methods based on computer vision are currently under extensive investigation but are still of very limited utility [3].

The aforementioned methods offer a wide variety of possibilities for studying human movement. However, these techniques, whose basic principles are well known since long ago, share limitations as described above. Therefore, it is beneficial to explore fundamentally new approaches that would solve some of the open problems and also stimulate further development in the field (out-of-the-box thinking). In this study we thus propose a novel method to address the problem of assessing body segments orientation in space. The method is based on the use of passive Radio Frequency Tags (RFID). It has to be noted that although RFID has been previously used for some biomedical applications (e.g., see [4] and [5]), these previous studies all applied RFID in the classical context, i.e., for object identification and gross localization. Conversely, in this paper we propose for the first time the use of dual polarized antennas to capture the polarization profile of UHF

RFID tags in order to record the actual orientation in space of human segments/joints during movement (i.e., human motion capture). This approach is therefore fundamentally different from the previous biomedical applications of RFID, both for the way in which the sensor signals are processed and used (i.e., estimating the tag orientation in space instead of reading the tag ID) and for the final type of information extracted (i.e., motion capture instead of gross body localization). The method that we propose (i.e., polarization profile measurement) was initially applied in a static context unrelated to human motion capture [6]. The goal of the present study is to provide a proof of concept of the feasibility of measuring joint angles during human walking using a fundamentally new methodology with respect to the current efforts in this field.

II. PROPOSED METHOD

We focus on the movement in the sagittal plane of a single leg during walking. The thigh and shank are equipped with Radio Frequency IDentification (RFID) tags, denoted T and S respectively, as illustrated in Fig. 1. The absolute angle of the individual leg segments with respect to the horizontal axis is obtained from the inclination of the tags, θ_t and θ_s. The inclination can be determined by estimating the polarization angle of the RFID tag response signals.

The tag antennas have a single linear polarization, hence the direction of the electric field backscattered from the tag antenna follows the longitudinal degrees from end to end of the antenna conductor. Using a dual polarized reader antenna we decompose the Received Signal Strength (RSS) of the tag response y_i, where index i belongs to $\{s, t\}$, into horizontal and vertical dimensions, termed y_{iH} and y_{iV} respectively. The estimated polarization angle is then $\hat{\theta}_i = \arctan\left(\frac{y_{iV}}{y_{iH}}\right)$.

III. EXPERIMENTAL SETUP AND DATA PROCESSING

To evaluate the proposed method, the leg movement was simultaneously measured using an RFID system and an optical motion capture system, while a male subject (h: 187 cm, w: 68 kg, 28 yrs.) was walking on a treadmill at a constant speed of 2.4 km/h (slow walking) and 4.8 km/h (normal walking). After warming up, the subject walked 5 min at each speed. The subject held his hands above the hips (elbow flexed) in order not to occlude the RFID tag placed on the thighs. The experiment was approved by the local ethical committee.

The RFID system comprised an Impinj Speedway Revolution Reader [7] and a single dual polarized antenna. The antenna was positioned to a similar height as the knee at a distance of 80 cm from the subject. This distance was selected due to a limited space available, although the actual range of the UHF RFID is much larger (several meters). The reader antenna was oriented with an observation angle normal to the sagittal plane. The tags were Alien "Squiggle" tags, since they have small dimensions (94.8 × 8.15 × 0.25 mm) and good dipole characteristics [8]. They were attached to each leg segment with the long tag axis aligned with the longitudinal segment axis. The RFID tags were placed on a 30 mm thick plastic support which was secured to the leg segments using a double sided tape. This plastic support, transparent to the electromagnetic field, was used in order to reduce the effect of biological tissues on the electromagnetic radiation. During walking, the shank and thigh segments are mainly vertical, i.e., the long segment axes rotate within the second and first half of the III and IV quadrant of the world coordinate system CSW (lab horizontal and vertical), respectively. The long axis of the tag is aligned with the long axis of the segment, and the tag antenna therefore moves identically. In order to obtain a good response from each tag in both dimensions of the dual polarized reader antenna, the reader antenna was rotated by $+45^\circ$. By using this configuration, we avoid 100% polarization mismatch and bias towards the vertical component response. The tag antenna now moves through the III quadrant of the slanted coordinate system of the reader antenna (CSRA), and the polarization changes symmetrically along both axes. However, since the power levels are positive, the estimated angles are always obtained as if they belong to the first quadrant of CSRA. To obtain the angles in CSW, constant offsets have to be added, i.e., 180 degrees to map the angle from the I to III quadrant of CSRA followed by 45 degrees for the shift from CSRA to CSW, hence:

$$\hat{\theta}_i = \arctan\left(\frac{y_{iV}}{y_{iH}}\right) + 180^\circ + 45^\circ \quad (1)$$

The reader samples each tag with a sample rate of about 25 Hz, and the interrogation is based on the EPC Global Gen2 protocol [9]. The order of identified tags is thus random, and it is necessary to match the samples in order to ensure that the inclination estimates are based on vertical and horizontal samples with approximately the same time stamp.

The optical motion capture system used for reference (ProReflex cameras, Qualisys AB, Sweden) included eight infrared cameras encircling the treadmill. Reflective markers were attached using a double sided tape to the hip knee and ankle joints of the left leg. The sampling rate for the camera system was set to 100 Hz. From the recorded joint trajectories, we derived the absolute, sagittal plane angles for the thigh and shank segments with respect to the horizontal. The angles were filtered by a first order zero phase shift Butterworth filter with the cutoff frequency of 6 Hz [10].

The estimated segment angles were checked visually and outlier points, which occurred very rarely, were manually deleted. As described above, the estimated angles are mapped to the world coordinate system. We have observed two additional systematic errors. The estimated thigh angle overshot the reference signal, and there was a slight phase shift of few samples between the estimated and reference signals for both angles. These discrepancies were consistent during the measurement and thus they were corrected by time-aligning and rescaling the signals according to the reference system.

For direct comparison with the reference results, the estimated angles were up-sampled to 100 Hz by using linear interpolation and then filtered by the same filter as the reference signals. The obtained smoothed angles were considered as the final outcome of the measurements.

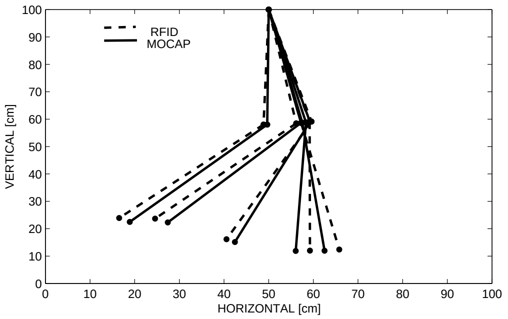


Fig. 2. Stick figure model of the recorded walking for a swing phase of a gait stride. The estimated (RFID) and reference (cameras) model snapshots are shown with dashed and solid lines, respectively. The two configurations are close together throughout the movement.

TABLE I

PERFORMANCE SUMMARY

	Slow (2.4 km/h)		Normal (4.8 km/h)	
	CORR	MAE (STD) [°]	CORR	MAE (STD) [°]
Thigh	0.93	3.2 (2.9)	0.98	2.59 (2.59)
Shank	0.91	5.7 (5)	0.93	6.66 (5.41)

CORR (Cross Correlation Coefficient), MAE (Mean Absolute Error), and STD (Standard Deviation).

To evaluate the quality of the measurements by the new system, we calculated the cross correlation coefficient (CORR) and the mean absolute error (MAE) between the angles estimated using RFID tags and the angles recorded by the motion capture system (reference).

IV. RESULTS

Representative results are shown in Figs. 2 and 3. Fig. 2 illustrates the spatial precision of the measurement. It shows several snapshots of the subject leg during the swing phase of a representative gait stride. The estimated configurations are close to the reference ones and the error in joint positions is less than a few centimeters. The error increased from proximal to distal locations. The average absolute distance error (standard deviation) was 1.5 cm (± 1.2 cm) for the knee and 2.8 cm (± 1.5 cm) for the ankle joint.

Fig. 3 depicts six strides that were recorded at the walking speed of 2.4 km/h. Panels 3(a) and 3(b) represent the estimated angles with random and systematic errors corrected. Panels 3(c) and 3(d) are the resampled and smoothed signals that are the final outputs of our measurement. Note that the RFID system uses sparse and non-equidistant sampling. Nevertheless, the output follows the angle trajectory. This is an important result demonstrating that the polarization profile actually contains the information of interest. The task of the future steps will be to refine the extraction of this information. Furthermore, the final outcomes, i.e., the smoothed signals, closely track the reference value. It should be noted that the tracking is worse around the limits of the reference signals.

Table I reports a summary of the results as CORR and MAE computed for the entire walking trial. The cross-correlation coefficients were higher than 0.9 in all cases, and the thigh angle estimation was more accurate than the shank angle. The estimation accuracy was similar at both speeds.

V. DISCUSSION

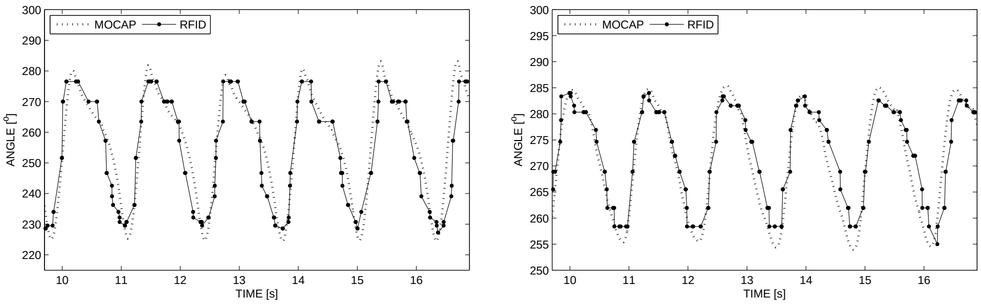
In this work, we have demonstrated the feasibility of a radically novel approach for measuring human movements. The trajectories of the shank and thigh segments during walking were successfully recorded, and this was done with a good accuracy (Table I). The performance should be evaluated by taking into account that the method is in its initial phase of development. The goal of this study was to provide a first proof of concept of the approach, and the task of the subsequent research will be to refine the accuracy (see below). The current precision is not high enough for a rigorous biomechanical analysis, but even at this stage, the method could be used in some applications for which high precision is not critical (e.g., electrical stimulation triggering). Overall, the first tests are very promising since the current results were obtained with basic components and a simple heuristic model with no assumptions on the nature of the signal to be estimated. Therefore, the precision can be improved significantly by further developments in hardware and software, optimizing the sampling and decision procedures, as indicated below.

As indicated in section III, there was a difference in phase between the estimated and reference angles. This is due to a slight time mismatch between the samples collected by two orthogonal reader antennas, introducing a systematic error in the estimated angle, which appears as a phase shift. Moreover, in some cases the estimated angle overshot the reference values. This is likely due reflections and nonlinear inverse tangent function (equation (1)). The change in received power is thus non-proportional to the change in angle. However, the influence of these effects can be minimized by a special antenna design or in the post processing of the data.

The presented setup is practical and only requires placing the passive tags along the segments of interest. The plastic separation can be reduced significantly by designing an application specific antenna. Therefore, the tags, which are very thin, can be integrated within a motion capture suit. However, this is outside the scope of this work.

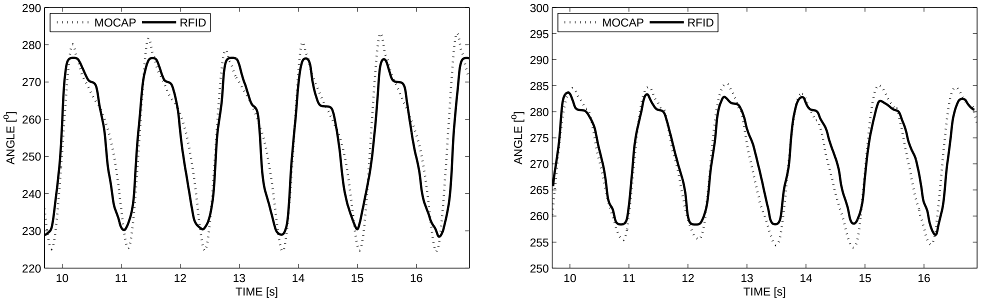
The main advantages of the proposed system over the existing methods are simplicity, low cost and the way each leg segment is marked with the unique ID from the RFID tags. Hence, the data is directly coupled with the correct segment. This property of the proposed system is particularly important since automatic marker identification in optoelectronic systems with passive markers is an open problem [1], [11].

As can be seen in Fig. 3, the direct output of the RFID system is non-smooth, but this is only due to the technical limitations of the currently used equipment. The sampling rate ($\sim$ 25 Hz) and resolution of RSSI measurements ($\sim$ 1 dBm) were relatively low [10]. The recorded RSSI during subject walking was in the range from -66 to -45 dBm. The mapping from RSSI levels to angles is nonlinear, and the resolution (delta RSSI to delta angle) depends on the ratio between the horizontal and vertical power components, i.e., the angular change for a change of 1 dBm in either component can range from less than a degree to a few degrees (for components



(a) Estimated shank angle.

(b) Estimated thigh angle.



(c) Smoothed shank angle.

(d) Smoothed thigh angle.

Fig. 3. Thigh and shank segment angles recorded using RFID tags (solid line) and motion capture system (dashed line). The panels (a) and (b) depict the direct outputs of the RFID system while the panels (c) and (d) are the up-sampled and smoothed versions of these signals. Note that the estimated signals follow well the reference patterns.

similar in size). The next step in the development of the system hardware is to increase the fidelity of the recording by increasing the precision of the sensing antenna and also by increasing the speed/rate of tag readings. The latter can be done by using a custom designed tag reader.

Parallel to the hardware development, it will be necessary to refine the precision of the system by developing more sophisticated estimation techniques that would use prior information, more signal samples and/or sensor fusion methods (e.g. Kalman filtering) to refine the estimate.

In this experiment, we have used a single dual polarized antenna to capture planar motion, i.e., the motion of the tag in the sagittal plan. In this setup, the out of plane motion of the tag affects the estimation by introducing a polarization mismatch in the two dimensions observed by the antenna. To account for this distortion, multiple reader antennas observing the tags from multiple directions can be used, This might enable reconstruction of the tag orientation in multiple planes (i.e., full 3D capture). The goal of the current study was to test the feasibility of the method, using the simplest scenario.

In conclusion, we have demonstrated the potential of a radically novel method for detecting human movements. The true performance and capabilities of the novel technology are yet to be tested. Even if it may not be possible to achieve a precision similar to optoelectronic systems, further research efforts following this proof of concept could lead to a very practical, simple and low cost system. The novel solution would bring a number of unique features with respect to the currently used technology (e.g., automatic identification, sensors seamlessly integrated into the mocap suit). Depending on the obtained performance, this research can lead to a general purpose motion capture system (e.g., gait recording and analysis) or an application specific solution (e.g., electrical stimulation triggering). In both cases, it would be an important addition to the current state of the art.

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