Sensor fusion for complex articulated body tracking applied in rowing

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I. MOTIVATION AND RELATED WORKS

The use of body tracking for quantitative assessment of subject performance is one of the basic elements of technology assisted training.

While traditionally body tracking has been based on optical systems [1], outdoor tracking can exploit wearable inertial based measurement systems. Wearable systems present interesting opportunities in the activities in which there is not a defined working area. In addition, they do not suffer from the occlusion and light problems typical of the optical systems. The solution of inertial system for human motion tracking have been successfully explored in [2], to track the human upper limb, comprising the shoulder girdle and elbow joints.

In sports in which the subject performs its activity over a structure, such the boat in rowing, it is possible to combine sensors on board of the structure with wearable sensors. For the rowing case several research efforts have been dedicated to create instrumented boats for assessing the performance of the rowers by measuring the dynamics of the boat and the motion of the oars. Recent examples are the SonicSeat [3] that employs ultrasonic sensors for seat tracking, or [4] and [5] that tracked seat and oars by means of inertial units. We present a wearable inertial tracking system for outdoor rowing training, complementing the performance assessment typically performed with the measure of seat and oar motion. We introduce in the model a closed kinematic chain to further increase the tracking performance of the system. In comparison to camera based setups this approach is suitable also for outdoor measurements with minimal encumbrance for the subject.

II. METHODS

Motion reconstruction is based on an Unscented Kalman Filter. The filter fuses measurements from the 5 IMUs placed on rower's arms, forearms and back, and from the rowing platform sensors that provide seat position and oar angles. The system is composed of two kinematic chains, as shown in Figure II. The first represents the rower's upper body including pelvis, back, arms and forearms. The pelvis slides along the platform rail, the back has the flexion DoF with respect to the pelvis, shoulder provides 3 DoFs and the forearm has 2 DoFs with respect to the arm. The second chain is composed of the two oars each one having two rotational DoF with respect to the fixed reference frame [6]. The Kalman filter is based on the following models:

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$$\begin{cases} \dot{x}_i = f(x_i) \quad i = 1, \ldots, 16 \quad \text{State model} \\ y_j = h(x) \quad j = 1, \ldots, 60 \quad \text{Measurements model} \end{cases} \tag{1}$$

The state part related to the rower arms is composed of two sets of 7 DoF as in [2] whereas only wrist positions are included. The measurement model components related to the inertial sensors are described in [2]. We exploit and impose the closure of the two kinematic chains by considering that the seat position correspond to the rower pelvis position and the tip of the oar handles positions and orientations match the rower's wrist poses. The former constraint is

$$h_1(x) = x_1, \tag{2}$$

the latter constraint take into account all the three components of the position and the matching between the oar axes and the rower wrist flexion axes:

$$h_{2:4} = r^0_{0,9} - r^0_{0,21} \tag{3}$$

$$h_{5:8} = (T_9)_x - (T_{21})_z \tag{4}$$

$$h_{9:11} = r^0_{0,16} - r^0_{0,25} \tag{5}$$

$$h_{12:14} = (T_{16})_x - (T_{25})_z \tag{6}$$

where T_i is the global transformation matrix between the reference fixed frame and $i-th$ frame and $r^k_{i,j}$ is the position vector of frame $j - th$ with respect to frame $i - th$, written in $k - th$ reference frame.

These latter constraints are included as they are supposed to improve the rower motion estimation with respect to ignoring the rowing platform kinematics.

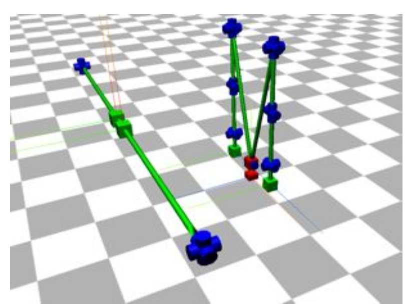

Fig. 1. Kinematic model. All the joints are in the rest pose (N-pose)

III. RESULTS

First we validate the system using simulated data. We generate simulated trajectories from pre-processed data from real-word captures and adding Gaussian white noise.

Joints	RMS	Joints	RMS
q_1 $[m]$	0.107	q_7 $[deg]$	0.203
q_2 $[deg]$	0.326	q_8 $[deg]$	0.134
q_3 $[deg]$	0.118	q_9 $[deg]$	0.193
q_4 $[deg]$	0.220	q_{10} $[deg]$	0.306
q_5 $[deg]$	0.382	q_{11} $[deg]$	0.282
q_6 $[deg]$	0.329	q_{12} $[deg]$	0.172

TABLE I

RMS FOR ALL THE JOINTS IN THE KINEMATIC MODEL WITH SYNTHETIC SENSORS MEASUREMENTS.

Secondly we validate the system performing an experiment over the SPRINT rowing simulator system with the seat position provided by a wire potentiometer Posiwire® ws31C. This type of acquisition device is the same as employed for the instrumentation of a boat [6].

The participant was provided with 5 inertial units MPU9150 (Invensense, Borregas Ave Sunnyvale, CA, USA) placed on the back and left and right upper arm and fore arm, communicating via Bluetooth to an acquisition pc. The reference information was provided by the marker based motion capture system. The experimental setup is shown in Figure III.

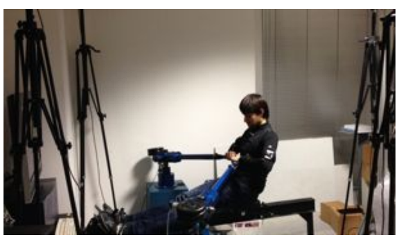

Fig. 2. Experimental Setup

Firstly the participant was instructed to perform a three-step calibration procedure needed to compute the inertial sensors orientation and calibrate the magnetometers. Then, he was asked to perform multiple sequence of rowing strokes, while being tracked both by the optical and inertial tracking systems. Data were captured for two 40 seconds trials in which the participant was asked to focus on rowing technique. In Table II for every position considered (elbows, wrists and hands) is shown the RMSEs against optical data.

Position	E_p	Position	E_p
p_{ShR} $[m]$	0.078	p_{ElL} $[m]$	0.153
p_{ShL} $[m]$	0.081	p_{WrR} $[m]$	0.034
p_{ElR} $[m]$	0.158	p_{WrL} $[m]$	0.054

TABLE II

E_p, FOR THE POSITIONS CONSIDERED: RIGHT SHOULDER (p_{ShR}), LEFT SHOULDER (p_{ShL}), RIGHT ELBOW (p_{ElR}), LEFT ELBOW (p_{ElL}), RIGHT WRIST (p_{WrR}), LEFT WRIST (p_{WrL})

We also report the comparison between of our algorithm and the optical tracking system in Figure 3 to show how the algorithm performs.

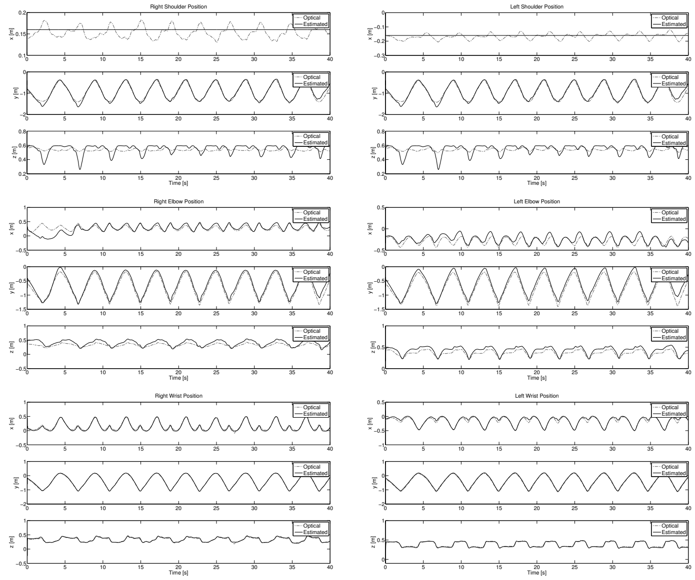

Fig. 3. Motion tracking results obtained with the inertial tracking system algorithm for the first rowing trial (Shoulder, Elbow and Wrist positions).

IV. CONTRIBUTION TO THE WORKSHOP

We presented a wearable solution for motion tracking in outdoor training for rowing. The classical approach exploiting inertial sensors have been expanded considering the fusion between inertial sensors on the subject body and sensors available on the sensorized boat. The fusion have been obtained exploiting the potentiality of the Unscented Kalman Filter, and closing the kinematic loop between the rower and the oar kinematic chains through the measurement model. The validity of the approach have been assessed with tests both with simulated and real data.

REFERENCES

[1] S. Barris and C. Button, “A review of vision-based motion analysis in sport,” *Sports Medicine*, vol. 38, no. 12, pp. 1025–1043, 2008.

[2] L. Peppoloni, A. Filippeschi, E. Ruffaldi, and C. A. Avizzano, “A novel 7 degrees of freedom model for upper limb kinematic reconstruction based on wearable sensors,” in *Intelligent Systems and Informatics (SISY), 2013 IEEE 11th International Symposium on*. IEEE, 2013, pp. 105–110.

[3] F. Gravenhorst, C. Thiem, B. Tessendorf, R. Adelsberger, B. Arnrich, C. Draper, R. Smith, and G. Traster, “Sonicseat: design and evaluation of a seat position tracker based on ultrasonic sound measurements for rowing technique analysis,” *Journal of Ambient Intelligence and Humanized Computing*, pp. 1–10, 2014. [Online]. Available: http://dx.doi.org/10.1007/s12652-013-0216-5

[4] F. Gravenhorst, T. Turner, C. Draper, R. M. Smith, and G. Troester, “Validation of a rowing oar angle measurement system based on an inertial measurement unit,” in *Trust, Security and Privacy in Computing and Communications (TrustCom), 2013 12th IEEE International Conference on*. IEEE, 2013, pp. 1412–1419.

[5] B. Tessendorf, F. Gravenhorst, B. Arnrich, and G. Troster, “An imu-based sensor network to continuously monitor rowing technique on the water,” in *Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP), 2011 Seventh International Conference on*. IEEE, 2011, pp. 253–258.

[6] A. Filippeschi and E. Ruffaldi, “Boat dynamics and force rendering models for the sprint system,” *Human-Machine Systems, IEEE Transactions on*, vol. 43, no. 6, pp. 631–642, 2013.