ARTICLE IN PRESS

Control Engineering Practice xx (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

A low-cost high-fidelity ultrasound simulator with the inertial tracking of the probe pose

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ARTICLE INFO

Keywords:
Inertial tracking
Ultrasound simulator
Sensor fusion
Medical training
Real-time algorithms

ABSTRACT

The authors developed a versatile ultrasound simulator. The proposed system achieves the main features of a high-fidelity device exploiting low-cost rapid prototyping hardware. The hand-guided ultrasound simulator probe includes a RFID reader, a 9-DOF inertial sensor unit, consisting of an accelerometer, a magnetometer and a gyroscope, and a microcontroller that performs the real-time data acquisition, the processing and the transmission of the estimated pose information to the visualization system, so that the proper ultrasound view can be generated. Since the probe orientation is the main information involved in the pose reconstruction, this work presents and investigates several tracking methods for the probe orientation, exploiting a sensor fusion technique to filter the noisy measurements coming from inertial sensors. The performances of a Kalman filter, a nonlinear complementary filter and a quaternion-based filter as inertial trackers have been tested by means of a robot manipulator, in terms of readiness, accuracy and stability of the estimated orientation signal. The results show that the nonlinear complementary filter and the quaternion-based filter match all the application requirements (RMSE <3 deg, variance $<1\mathrm{deg}^2$, and settling time <0.3 s), and they involve a lower computational time with respect to the Kalman filter.

1. Introduction

In the last decades, lots of studies have demonstrated the importance and the usefulness of simulation in medical training and education, in particular in the field of emergency medicine, where operators need to practice on critical cases without endangering the patient's health (Parks, Atkinson, Verheul, & LeBlanc-Duchin, 2013). A novel valuable tool, for providing an early diagnosis on trauma, concerns the use of point of care ultrasonography (POCUS), consisting in the acquisition and the evaluation of a series of ultrasound (US) scans focused on particular landmark of interest, such as the lungs or the heart (Vignon, 2012). The standard procedures described in the focus assessment with sonography for trauma (FAST) protocol are specifically introduced to facilitate the detection of free fluids (Gillman, Ball, Panebianco, Al-Kadi, & Kirkpatrick, 2009). A consequence of the larger diffusion of US scanners is the fact that more and more emergency operators have to be trained on their use (Oxorn & Pearlman, 2012). Moreover, US scanners used on the field cannot be used for training, because of their cost. Therefore, the biomedical industry has recently marketed many devices, capable of simulating an ultrasonography scenario, with different characteristics and features, as reported in Blum, Rieger, Navab, Friess, and Martignoni (2013). Taking into account the requirement of low-cost, high-fidelity and user-friendliness the authors designed a versatile US simulator comprehensive of the main advantages of the currently available systems, as well as novel features regarding the visualization of US data sets, the graphical interfaces adapted for education sessions and the extensible database. A prototype of the simulator is described in Farsoni, Astolfi, Bonfé, and Spadaro (2015). The crucial point for the proper behavior of the system is the tracking of the simulator probe: i.e. the device reproducing the US transducer. Indeed, the real-time information about its current pose (understood as the merging of position and orientation) relative to the phantom is exploited by the visualization system in order to display the appropriate US view.

This problem can be addressed as the reconstruction of the pose of a rigid body (the probe) relative to another rigid body (the phantom), both moving in the Earth Reference System. Indeed, also the phantom can be voluntarily moved, or even accidentally bumped during the simulation, causing the alteration of the relative reference system. The tracking issue interests many engineering domains including robotics and aerospace as well as simulation and virtual reality, and their applications involve different motion characteristics: the body accel-

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http://dx.doi.org/10.1016/j.conengprac.2016.11.002
Received 13 November 2015; Received in revised form 23 August 2016; Accepted 1 November 2016
Available online xxxx

eration can range from the low values of a human hand to several times the gravity acceleration in an aircraft. The tracking systems discussed in Welch and Foxlin (2002) are categorized depending on the exploited technology: optical, image-based, mechanical, magnetic, inertial, acoustic, and hybrid systems represent a wide range of opportunities to overcome the problem, with different costs, sizes and performances. The inertial sensor trackers rely on the data acquired by microelectromechanical system (MEMS) based accelerometers, magnetometers and gyroscopes and they meet the US simulators scope in terms of cheapness and size (Serrano & Ayazi, 2015). However, the electronic offsets and drifts of this kind of sensors yield significant tracking errors during the integration of linear acceleration and angular rate, so that a dynamic pose reconstruction exploiting the numerical integration of acceleration (for the position) and angular rate (for the orientation) is impossible unless introducing an external reference, as pointed out in Luinge and Veltink (2005). The common solution is a sensor fusion algorithm that combines together the information coming from different inertial sensors.

Considering the requirements of the POCUS simulation, the reconstruction of the probe position can be solved using the RFID technology, by discretizing the phantom body in several landmarks of interest, as described in Section 2. The tracking of the probe orientation involves the acquisition and filtering of noisy measurement from the accelerometer, the magnetometer, and the gyroscope and represents the challenging task to overcome. The proposed solutions, described in Section 3.2, exploit two inertial tracking systems, one fixed to the phantom and another one fixed to the probe. Both the tracking systems estimate the orientation relative to the Earth Reference System (ERS), so that the probe orientation relative to the phantom can be calculated as the rotation required to align the systems.

This paper extends the work of Farsoni et al. (2015) by briefly presenting the updated hardware and software implementation, which is described in Section 2. Furthermore, the novel contribution of the work is a complete study concerning the inertial tracking of the probe orientation. Indeed, the usage of the prototype induced further investigations about the proper tracking method, since tracking errors, as well as tracking delays, strongly depend on the algorithm that processes the sensor measurements. In Section 3, after a brief introduction about how inertial sensors such as gyroscope, accelerometer and magnetometer can produce the orientation estimation, three sensor fusion tracking algorithms are presented. Then, Section 4 addresses the comparative assessment of the considered algorithms. Section 5 makes some considerations about the obtained results, highlighting the motivations that support the final choice of the algorithm implemented on the system. Finally, Section 6 summarizes the overall development of the simulator.

2. System components

In this section the hardware and software development of the simulator is briefly summarized, highlighting the improvement and the difference with respect to the previous prototype implementation.

2.1. Hardware

In order to create an economically sustainable system, all of the hardware components are chosen with the aim to increase the performance/cost ratio. The list of components can be found in Table 1.

The design of the probe involves a microcontroller that accomplishes different tasks: firstly, measurements are acquired from the RFID reader and from the inertial sensors, then the elaboration of the tracking algorithm is performed and the information on the probe pose is real-time communicated to the visualization system. The RFID reader is located at the bottom side of the probe. It acquires the codes of a set of markers, typically nine, positioned under the phantom skin, in agreement with the point of care described in FAST procedure. When the reader enters in the field of a marker, the identification (ID) code uniquely associated to the marker is read. Since for each marker its location with reference to the phantom is known, the ID code specifies also the position of the probe on the phantom skin. The distance between tags should be at least 3 cm, in order to avoid the acquisition of the wrong ID code. The chosen component is the Innovation ID-12LA, which differs from the prototype RFID reader of Farsoni et al. (2015) in terms of a lower input voltage and a wider read range, although it maintains the same size.

Table 1
The hardware components of the simulator probe.

Device	Board/ Component	Features
Microcontroller	Teensy 3.1	MK20DX256 32 bit ARM Cortex-M4 processor, 64k RAM
Inertial sensor unit	Invensense MPU-9150	3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer, Fast Model I2C
RFID reader	Innovation ID-12LA	125 kHz read frequency, EM4001 64-bit tags, 9600 bps TTL output

Another important hardware upgrade concerns the microcontroller, the previous choice of Arduino Nano did not satisfy the requirement of the application in terms of stability, as one UART had to be shared between the RFID reader and the visualization system, often producing communication errors. The Teensy 3.1 is a recent low-cost microcontroller featuring three UARTs, suitable for implementing the TTL data communication up to three devices. Also the core, a MK20DX256 32 bit ARM, ensures better performances during the tracking processing, and a larger amount of memory allows the deployment of the sensor calibration code within the elaboration algorithm script.

The firmware running on the microcontroller executes repeatedly a main loop consisting of six successive acquisitions from inertial sensors, with the corresponding estimations and transmissions of the probe orientation to the visualization system. Afterwards, the microcontroller performs the acquisition and the transmission of the RFID code and another loop can start. The previous microcontroller mean loop time was 285 ms, while the Teensy mean loop time is decreased to 180 ms, allowing a faster response in the visualization of a US data set.

Finally, the inertial sensor Invensense MPU-9150 includes the three-axis MEMS sensors (the accelerometer, the gyroscope and the magnetometer) and communicates the measurements via I2C to the microcontroller. It is the same component exploited in the prototype, but the position inside the probe is different: it is located more distant from the bottom of the device in order to reduce the magnetic disturbances caused by the RFID reader and by the external sources. The shell of the probe can be built by a 3D printer, different shapes can be produced, based on user requirement. The probe and the inner components are shown in Fig. 1.

It is worth noting that the hardware required to track the phantom orientation has to be fixed to the phantom, and it consists of an inertial sensor unit and a microcontroller which acquires the measurements, executes the orientation estimation and transmits the information to the visualization system. The RFID reader is instead not included, because its information is only related to the position tracking and not to the orientation tracking. Once the current orientation of the probe and the current orientation of the phantom have been estimated, the rotation required for aligning the two systems can be calculated and the final information on the relative orientation is therefore provided. The overall system setup is depicted in the block diagram of Fig. 2.

2.2. Visualization software

The software has been developed for Microsoft.NET Framework to