

Design of an ultrasound simulator with probe pose tracking and medical dataset processing and visualization.

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Abstract: A high-fidelity, low-cost ultrasound simulator has been developed in order to improve the efficiency of ultrasound training, particularly in Focus Assessment by Sonography in Trauma (FAST). This examination is rapidly increasing its diffusion in Emergency Medicine, as it represents a quick tool for the detection of free fluids. The probe is the main component of the simulator as it provides the on-line tracking of its pose relative to the manikin representing the virtual patient. The proposed algorithm for the estimation of the probe orientation, a nonlinear complementary filter, is based on the fusion of information coming from inertial sensors. It is tested in static and dynamic conditions and its performances are compared with another traditional algorithm: the Kalman filter. Moreover, the software for the processing of medical dataset as images, videos and 3D volumes, has been developed in order to display the appropriate visualization on the simulator monitor. Finally, the simulator has been tested in a training session.

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Keywords: simulation, nonlinear filters, Kalman filters, attitude algorithms, inertial sensors, image processing.

1. INTRODUCTION

The acquisition of particular skills is often a long and difficult process and the way to reach good results is always obstructed by human faults and errors. Unfortunately, in medical environment errors are strictly forbidden, because human health can be in danger. In this mainframe, medical simulation is a tool that provides a model of the reality, thus allowing the safety evaluation and the interaction with the events that evolve from particular conditions fixed by users [Issemberg, 1999]. They can be standard condition, but also unusual condition, rarely occurring in real life.

The fidelity is the main parameter that describes the quality of a simulation. It is defined as the closeness to reality. Ideally, the best simulation is the one in which users cannot distinguish between reality and fiction.

In the last years, a growing attention to medical simulation has been paying by biomedical industry. The trade-off between low-cost and fidelity is the key-point. Low-cost and low-fidelity simulators consist of only software systems: they have a high degree of reality mismatch because of the absence of physical object representing the patient. On the other hand, a great realism is provided by very expansive high-fidelity simulators supporting full-scale simulation, where the whole patient and the scenario are realistic in every detail.

Skill-trainer simulators represent a good trade-off between these two extreme categories. They consist of anatomical models limited to the interested areas, allowing the training in a specific technique. The designed ultrasound simulator belongs to this category, as it emulates the ultrasound

examination. It is innovative and different with respect to other commercial device of same kind because of its feature of low-cost, high-fidelity, versatility and customizability, as described in Section 3.

It is particularly suitable in the mainframe of point of care ultrasonography, an ultrasound technique that is rapidly increasing its diffusion in emergency medicine. The relative examination is called Focus Assessment by Sonography in Trauma (FAST) and it allows the identification of pathology as hemoperitoneum, hemotorax, or cardiac tamponade. [Gilmann, 2008]. In this case, as generally in sonography, the quality of a scan is operator-dependent, as it reflects the experience and the degree of training. Recent studies have demonstrated that a number of 35/70 FAST examinations are required to gain proficiency with this technique and the learning curve becomes steady in 12/18 months [Ma, 2008]. Traditional medical teaching has many disadvantage as, first of all, the needs of volunteer patient with appropriate pathology. On the other hand, using the simulator, learners can interact in any moment with any desired clinical scenarios, without any risk for patient health. The proposed solution for a training session, as described in Section 3, consists of two separated environments, one for the instructor and another one for the learner. The instructor chooses the clinical scenario and evaluates the performance of the student. On the other side, the learner is immersed in the simulated reality and has to position and orientate correctly the probe on the desired manikin, in order to visualize the appropriate dataset on the simulator screen.

This work is organised as follows. Section 2 describes the implementation of the probe, the main device of the simulator,

with its hardware components and the algorithm exploited to track its pose (position and orientation). At the end of the section, comparisons between performances of different algorithms are reported. Section 3 describes the developed software for the processing and the visualization of ultrasound dataset as well as the applications for the instructor and the student. Finally, opinions of experts and learners are collected during a training session.

2. PROBE COMPONENTS AND MODEL

2.1 Hardware: sensors and microcontroller

The pose of the probe relative to the manikin is the goal information of the system. The inertial sensor platform consisting of accelerometer, gyroscope and magnetometer is the suitable solution in order to track the orientation of the probe. After a market survey, the best choice in terms of cost and size of the component has been the Sparkfun® MPU9150. The accelerometer together with the magnetometer give a static estimation of the orientation of a connected rigid body relative to Earth reference system, as they measure the inclination with respect to gravity and Earth's magnetic field vectors. Otherwise, gyroscope gives a dynamic estimation because it can reconstruct the variation in orientation as it provides measurements on angular velocity. Data from the inertial platform are redundant and they can be fused in order to estimate the orientation more accurately, as it is shown in the following. It is worth noting that another inertial platform is needed, connected to the manikin, as it provides the reference system for the probe orientation.

The position of the probe is simply tracked using a Radio Frequency Identification (RFID) reader inside the probe and a set of marker possibly located under manikin skin. In this way, there is a discretization of the position signal, as it is useful only in some point of interest. The suitable choice is represented by the component Innovation® ID-12.

Finally, a microcontroller, an Arduino® Nano [D'Ausilio, 2012], acquires data from sensors through I2C and Serial buses, and then the elaboration of all the data is computed so that the microcontroller can transmit to the application the on-line estimation of the pose. Also on this side, the communication exploits the serial bus.

The plastic shell containing all the components is easily built by a 3D printer and it looks like a real ultrasound probe.

2.2 Sensor fusion filter for estimation of probe orientation

An intuitive representation of the orientation of a rigid body is given by the Euler angles roll, pitch, and yaw. They are defined as the rotations around x,y,z-axes required to align the mobile body reference system to the fixed Earth reference system in which the three axes are supposed to point to north, east, down respectively.

In the related literature, many algorithms for the reconstruction of the orientation of rigid bodies were proposed, particularly

in aerospace, where this problem is known as Attitude and Heading Reference System (AHRS) [Luinge 1999, Madgwick 2010, Mahony 2008]. The algorithm exploited by the probe is similar to the one described in [Premerlani, 2009] but adapted to the requirements of the considered system. The algorithm is also known as nonlinear complementary filter (NCF) because its transfer function is the combination of a low-pass filter and a high-pass filter at the same cutting frequency [Hua, 2004]. A brief description of the algorithm is reported in the following.

The block diagram of the orientation estimator implementing the algorithm is represented in Fig. 1. Inputs are the measurements coming from sensors and output is the current estimation of the orientation in form of rotation matrix.

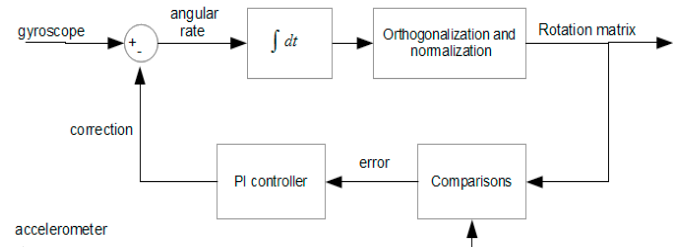


Fig. 1. Block diagram of the nonlinear complementary filter.

The noisy angular rates along each of the three Cartesian axes of the probe reference system are firstly acquired from the gyroscope as system inputs, and they are immediately corrected thanks to the elaborated feedback signal. Once the correction has been performed, the angular rates have to be integrated to estimate the variation in orientation. It is well known that a vector $\mathbf{r}$ rotating at an angular rate $\boldsymbol{\omega}$ has a variation equal to:

$$\frac{d\mathbf{r}(t)}{dt} = \boldsymbol{\omega}(t) \times \mathbf{r}(t) \quad (1)$$

This equation can be integrated in time, knowing the initial condition $\mathbf{r}(0)$:

$$\mathbf{r}(t) = \mathbf{r}(0) + \int_0^t \boldsymbol{\omega}(\tau) d\tau \times \mathbf{r}(\tau) \quad (2)$$

Then it is possible to discretize the time axis, supposing that $\boldsymbol{\omega}$ does not change between two consecutive time steps:

$$\mathbf{r}(k+1) = \mathbf{r}(k) + \mathbf{r}(k) \times \boldsymbol{\omega}(k)T_s \quad (3)$$

Where T_s is the sample time.

The three versors of a rotating system can be organized into the so-called rotation matrix, whose rows represent the versors of the probe system relative to the fixed manikin reference system. Equation (3) can be applied to the probe rotation matrix $\mathbf{R}$ obtaining:

$$\mathbf{R}(k+1) = \mathbf{R}(k) \begin{bmatrix} 1 & -\omega_z T_s & \omega_y T_s \\ \omega_z T_s & 1 & -\omega_x T_s \\ -\omega_y T_s & \omega_x T_s & 1 \end{bmatrix} \quad (4)$$

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