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Construction of a system scanning the movement of human upper limbs

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Abstract

The paper presents a prototype of a new input–output device which is a constructed scanner of human upper limb movement which, together with the software layer, creates a new user interface of CNC (Computer Numerical Control) machine tools. The constructed scanner contains a sensory system based on acceleration sensors and gyroscopes which are distributed within the key areas on the human upper limb. On the basis of the signals registered during the movement of operator's upper limbs, basing on the solution of a simple kinematics model, it is possible to determine the location and orientation of operator's hands. A combination of the developed technology with ready solutions of gloves scanning movements of fingers and hands provides a new intuitive input-output device for the communication with the machine.

Introduction

The development of the functionality of advanced mechatronic systems enforces research on the new communication forms between the operator and the machine. Since machines are not yet capable of communicating directly with humans, they are equipped with various input-output devices constituting the user interface.

The paper presents a constructed system scanning the operator's movements. This system, together with the software layer, creates the interface of a CNC machine tool operator. This interface, along with the use of virtual reality, allows for the manual programming of a machine tool (Fig. 1). Manual programming is based on moving the body elements of a machine tool manually by means of the operator's upper limbs and remembering individual positions, which allows for automatic reconstruction of movements.

The operator interface (Fig. 2) consists of input elements such as orientation sensors and a 3D Data Glove 4 Ultra on which there are five bend sensors – one sensor for each finger. An output element is a head-mounted display (HMD) which is a helmet with displays mounted on the head. Owing to the fact that the HMD is equipped with two separate

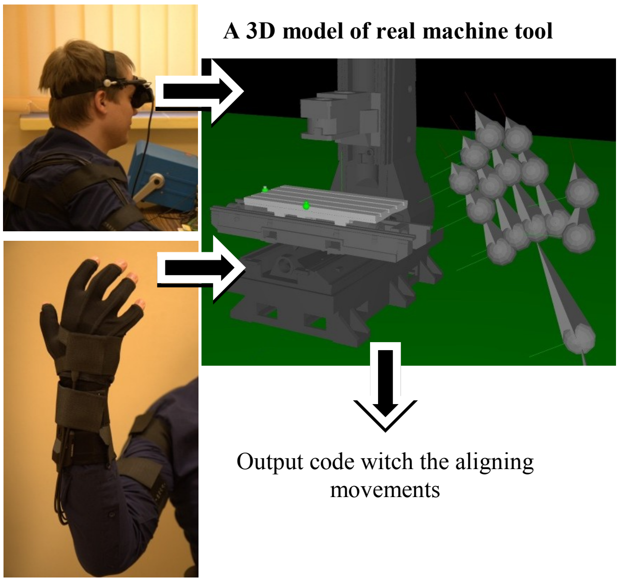

Fig. 1. Operator interface of a CNC machine tool

displays capable of displaying different images for each eye, it is possible to obtain the three-dimensionality effect when the displayed images are transposed appropriately. The entirety is managed by a custom application for a PC. It is responsible for the receipt of data, data processing and stereoscopic visualisation.

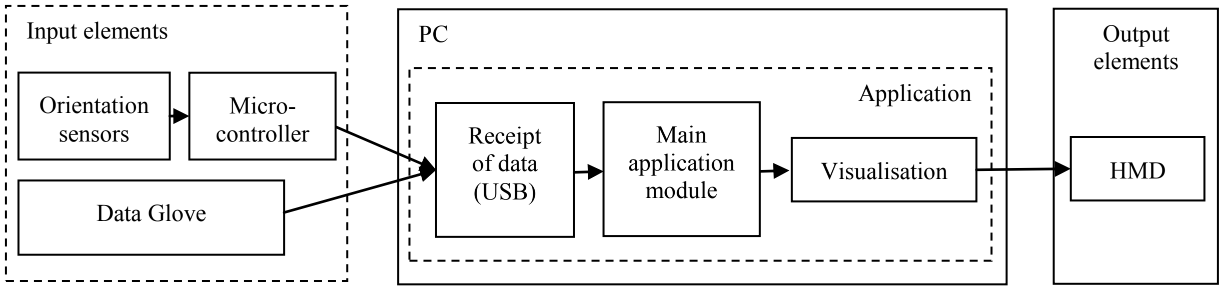

Fig. 2. Block diagram of the operator interface

System scanning the operator's movements

To map the movements of the human upper limb in the virtual reality, it is necessary to know the orientation of the arm, the forearm and the hand, and in order to map the movement more accurately, it is possible to additionally take into account the orientation of the shoulder and the back.

Orientation sensors

There are numerous methods for determining the orientation of an object in space, they have different advantages but also disadvantages, and therefore, different methods are applied in various fields of technology. Systems based on inertial sensors have the advantage over other systems in the way that they are mobile and self-sufficient, i.e. they do not require the deployment of additional equipment for measurements, e.g. cameras and lighting which is necessary in vision systems, transmitters and receivers as in the case of systems using infrared, radar and ultrasonic systems, as well as coils in the case of magnetic systems [1]. Thus, they are not limited by a specific environment, movement or location.

In this paper, author applied a technique using the acceleration measurements (including gravity) and angular velocity measured by means of an accelerometer and gyroscope respectively. These sensors made in the MEMS technology (Micro Electro-Mechanical System) are integrated in a complete inertial system ADIS16362. Its advantage is that it has a compensation of the input voltage impact and a compensation of the impact of temperature for each of the built-in sensors [2]. It is factory-calibrated sensitivity, bias and axial alignment.

A gyroscope measures the angular velocity, and knowing the initial conditions, it is possible to integrate the measured signal with the time in order to obtain the orientation. However, a measurement error leads to an error accumulation of the translated orientation which makes the determination of absolute orientation impossible. An accelerometer measures the earth gravity in an absolute system, but there are strong measurement interferences during its movement. In order to calculate orientation on the basis of measurements from the gyroscope and the accelerometer, author used the orientation filter [3] for the IMU (Inertial Measurement Unit) implementation, whose block diagram is presented in figure 3.

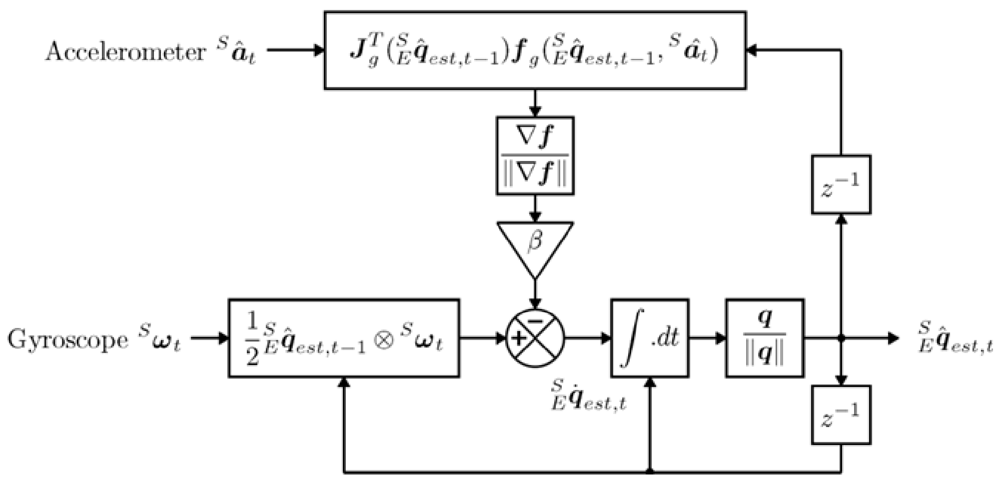

Fig. 3. Block diagram of the orientation filter for an IMU implementation [3]

This filter is characterised with a low computational cost, which enables its implementation on cheap microcontrollers. It achieves a higher level of accuracy in comparison with the Kalman filter applied for calculating orientation [3].

The filter was implemented on the STM32F103 CBT6 microcontroller on the ZL30ARM instruction set. Figure 4 presents the acceleration sensors along with the platform on which the filter is implemented. ADIS16362 sensors communicate with the microcontroller by means of an SPI interface (Serial Peripheral Interface), sending the acceleration and angular velocity values necessary for calculating the orientation by means of the filter. Orientation in space is represented by means of a quaternion. Data is transmitted to the computer by means of a USB interface.

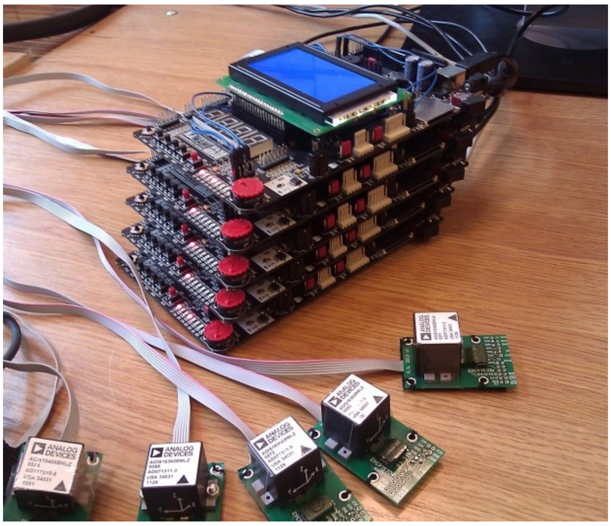

Fig. 4. Sensors along with the computing platform

A quaternion may be treated as four numbers and, similarly to the vector, it differs in the way of performing some arithmetic operations [4, 5]:

$$\mathbf{q} = [w, x, y, z] = w + ix + jy + kz \tag{1}$$

They are an extension of complex numbers and they may be written using three roots of –1 marked with the following symbols: *i*, *j*, *k*. If squared, they equal –1:

$$i^2 = j^2 = k^2 = -1 \tag{2}$$

It is often represented as a pair of the number *s* and a vector **v**:

$$q = [s, \mathbf{v}] \tag{3}$$

where: $s = w$, $\mathbf{v} = [x, y, z]$.

Unit quaternions are quaternions whose norm is equal to 1, and they can be represented as follows:

$$q = [s, \mathbf{v}] = \left[\cos\left(\frac{\theta}{2}\right), \sin\left(\frac{\theta}{2}\right)\mathbf{u}\right] \text{ where } |\mathbf{u}|^2 = \mathbf{u}^2 = 1$$

$$|q|^2 = \cos^2\left(\frac{\theta}{2}\right) + \sin^2\left(\frac{\theta}{2}\right)\mathbf{u} = 1 \tag{4}$$

A quaternion may be regarded as a representation of rotation where the vector determined the direction of axis rotation and the angle θ determined the angle by which the rotation has been made (Fig. 5).

$$\theta = 2\arccos(s) \quad \mathbf{u} = \frac{\mathbf{v}}{\sin\left(\frac{\theta}{2}\right)} \tag{5}$$

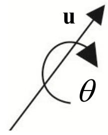

Fig. 5. Rotation by an angle around the vector **u**

It is possible to translate the quaternion to the rotation matrix unambiguously:

$$\begin{bmatrix} 1-2(y^2+z^2) & 2(xy-zw) & 2(xz+yw) \\ 2(xy+zw) & 1-2(x^2+z^2) & 2(yz-xw) \\ 2(xz-yw) & 2(yz+xw) & 1-2(x^2+y^2) \end{bmatrix} \tag{6}$$

Determining the position of segments

In the standard approach, e.g. in robotics, joint coordinates are measured to determine the location of segments (Fig. 6), i.e. the configuration angles of segments of the motion connection φ_i, $i = 1...n$ [6].

Then, the rotation matrices and homogeneous transformation matrices are constructed:

$$\varphi_i \rightarrow {}^{i}_{i+1}\Theta(\varphi_i) \mapsto {}^{i}_{i+1}\mathbb{F}(\varphi_i) = \begin{bmatrix} {}^{i}_{i+1}\Theta & \vdots & {}^{i}\mathbb{P}_{i+1} \\ \cdots\cdots\cdots & \vdots & \cdots \\ 0\ 0\ 0 & \vdots & 1 \end{bmatrix} \tag{7}$$

On this basis, it is possible to determine the position of segments:

$${}^{0}_{n}\mathbb{F}(\varphi_i \ldots \varphi_n) = \prod_{i=1}^{n} {}^{i-1}_{i}\mathbb{F}(\varphi_i) \tag{8}$$

In the designed system scanning the human movements, the MEMS measurement system returns the quaternions which describe the orientation in a global reference system (Fig. 7)

Rotation matrices and homogeneous transformation matrices are constructed:

$$\mathbb{q}_i \rightarrow {}^{0}_{i}\Theta(w_i, x_i, y_i, z_i) \tag{9}$$

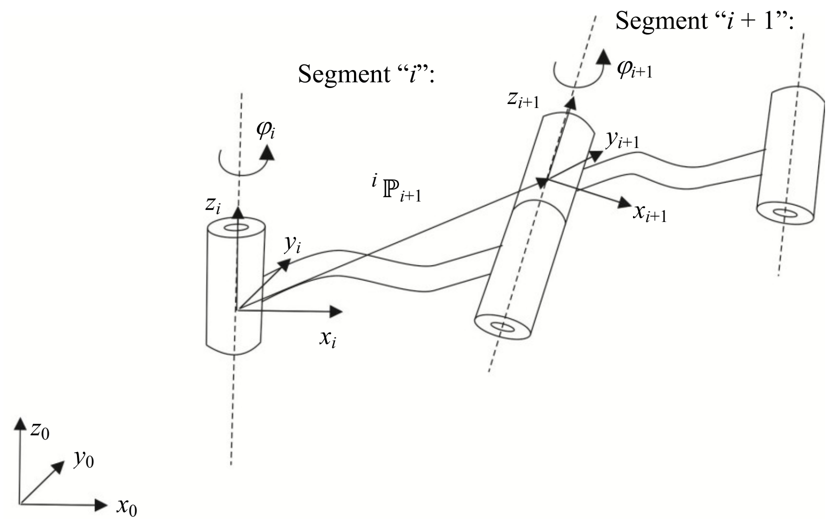

Fig. 6. Determining the position of segments, standard approach

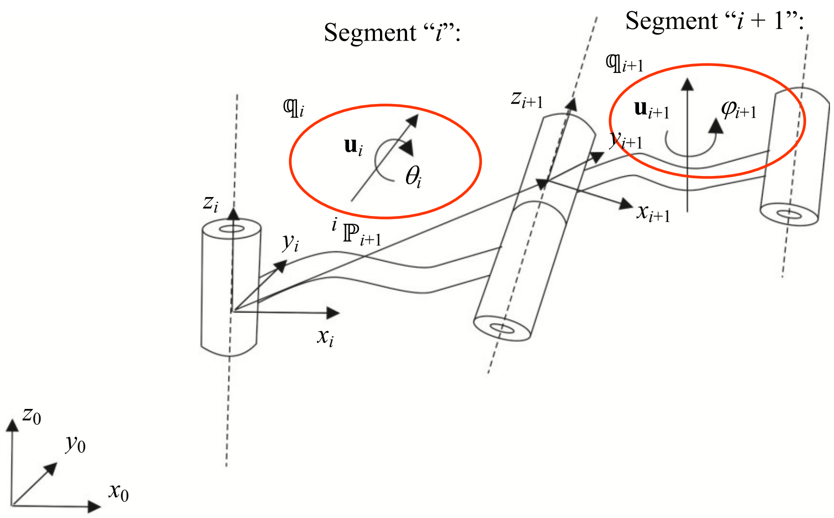

Fig. 7. Determining the position of segments, modified approach

$$
{}^{0}_{i}\Theta \rightarrow {}^{i-1}_{i}\Theta = {}^{0}_{i}\Theta \prod_{k=1}^{i-1} {}^{k-1}_{k}\Theta^{T} \rightarrow
$$

$$
\rightarrow {}^{i-1}_{i}\mathbb{F} = \begin{bmatrix} {}^{i-1}_{i}\Theta & \vdots & {}^{i}\mathbb{P}_{i+1} \\ \cdots\cdots & \vdots & \cdots \\ 0\;0\;0 & \vdots & 1 \end{bmatrix} \tag{10}
$$

The rotation matrix determined on the basis of the quaternion describes the orientation in the global reference system, thus, there is a need to translate the rotation matrix to the matrix in relation to the system of particular segments.

Then, as before, it is possible to determine the location of segments with the use of a homogeneous matrix:

$$
{}^{0}_{n} \; = \prod_{i=1}^{n} {}^{i-1}_{i} \; (\mathbb{q}_i) \tag{11}
$$

Skeletal animation

Having analysed the human skeletal system, author constructed a simplified operator model. Figure 8 presents a simplified diagram of the human skeletal system.

The entirety has been implemented in the constructed virtual environment using the OpenGL graphics library. For animation of the operator in the 3D space, author used a modified popular method of skeletal animation in which bones are arranged hierarchically forming a tree (a bone has one parent but it may have many child bones). In this way, the next position of the bone is determined on the basis of the position in relation to the parent bone, and therefore, it is not necessary to determine the position of bones in the scene reference system. Since in this method bones are interlinked, a change in the bone orientation or bone

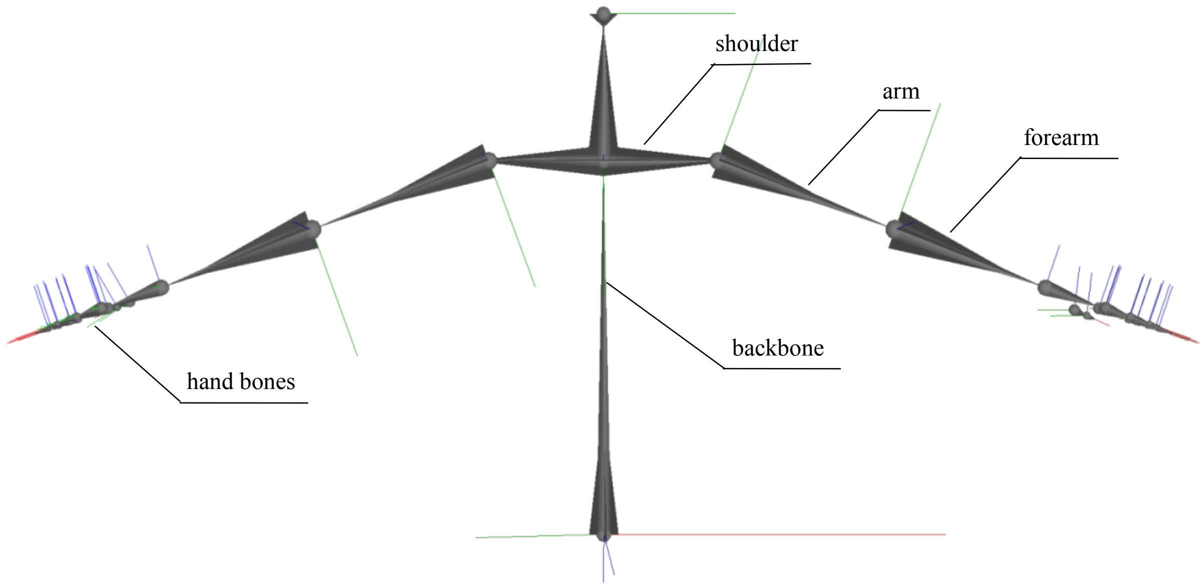

Fig. 8. Simplified diagram of the human skeletal system

position results in the change in orientation and position of all child bones of a given bone.

As mentioned above, orientation sensors provide information about the orientation of bones in the global system, and therefore, it was necessary to modify the given method, so that the position of the parent bone could have an influence on the orientation of a child bone and no influence on the child bone orientation (in the case of the shoulder, arm and forearm). Whereas, the bending of fingers is measured in the local system i.e. in relation to the previous bone, and therefore, the unchanged method of skeletal animation is used then. The algorithm is the modified method of skeletal animation is presented in figure 9.

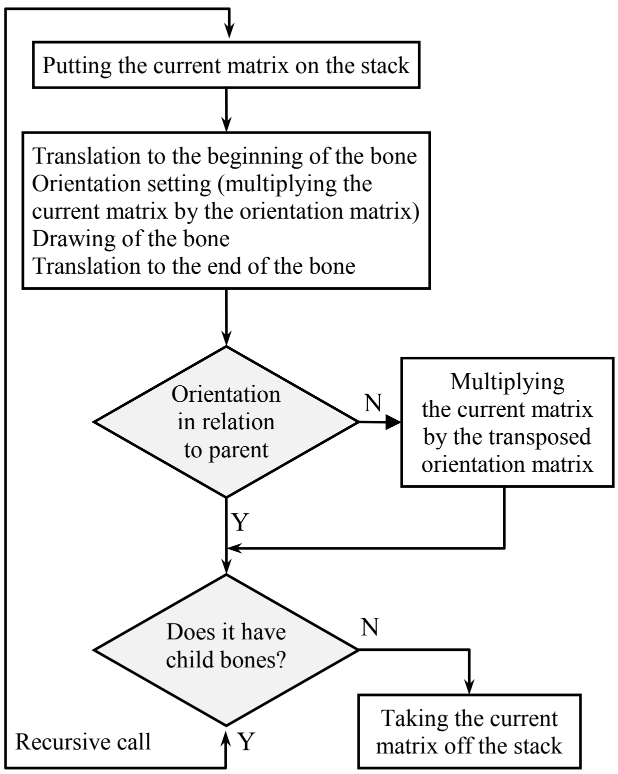

Fig. 9. Algorithm of modified method of skeletal animation

The sensors have been deployed on the operator's body taking into consideration the movement system of the human body muscles. Since it is impossible to position the sensors on each bone and determine their orientation, author constructed a simplified model of human kinematics and deployed sensors in strategic locations so as to unambiguously determine the position of hands in space.

It is worth noting that the written system takes into account the differences in the structure of different human bodies and enables entering the lengths of individual bones. In addition, it is possible to conduct periodic calibration during which it is possible to determine the initial orientation of the sensors, as presented in figure 10.

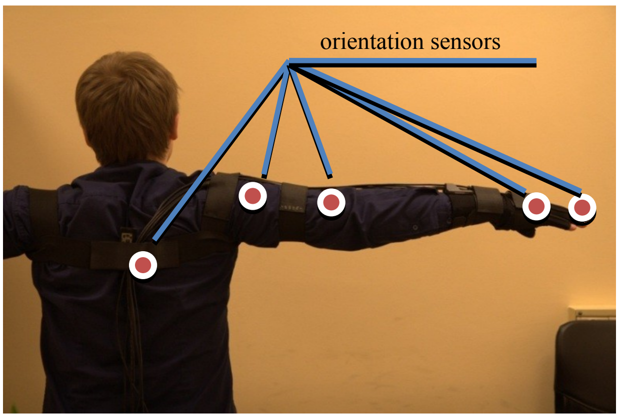

Fig. 10. Distribution of the orientation systems

Conclusions

The constructed scanner of the human upper limb movement can successfully be used in applications which involve virtual reality. The use of orientation sensors based on a MEMS gyroscope and an accelerometer causes a situation in which the deviation value during the work of the sensor is moved, thus requiring periodic calibration of the sensors. Better results can be achieved with the use of sensors with a magnetometer along with the extension filter for MARG (Magnetic, Angular Rate, and Gravity) implementation, described in the paper [3].

The constructed scanner of the human upper limb movement constituting the usage interface of a CNC machine tool in the application with a virtual technology and manual programming can facilitate and accelerate programming.

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