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INERTIAL SENSOR FRAMEWORK

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RESUMEN

Los sensores inerciales (IMU) contienen acelerómetros, giroscopios y/o magnetómetros en un solo chip, pueden medir posición tridimensional y velocidad angular, con respecto a los 3 ejes ortogonales XYZ. En este trabajo se evalúan dos sensores inerciales. Los sensores representan 2 generaciones de estos dispositivos. Se desarrolló una plataforma para la adquisición y procesamiento de los datos retornados por los inerciales, esto a través de varias bibliotecas y lenguajes de programación que permiten una importante capacidad gráfica. Se utilizan algoritmos de transformación para obtener la orientación del inercial.

Palabras Clave: Inercial, Razor, 3-Space, Rotación.

ABSTRACT

Inertial sensors (IMU) contain accelerometers, gyroscopes and/or magnetometers on a single chip, they can measure three-dimensional position and angular velocity, concerning the 3 orthogonal XYZ axes. In this work, two inertial sensors are evaluated. The sensors represent 2 generations of these devices. A framework was developed for acquiring and processing the data returned by the inertial, this through several libraries and programming languages that allow significant graphic capacity. Transformation algorithms are used to obtain the orientation of the inertial.

Keywords: Inertial, Razor, 3-Space, Rotation.

1. INTRODUCTION

Inertial sensors or Inertial Measurement Unit (IMU) refer to sensing technologies that use the property of inertia. They are small devices capable of measuring linear acceleration and angular velocity. They contain a combination of accelerometers, gyroscopes and/or magnetometers in a single electronic device.

These devices provide 3D three-dimensional measurements, accelerometer/gyrometer/magnetometer, on each of 3 axes of the device all in one. The IMU measures the angular velocity, specific force and surrounding magnetic field produced in a body.

The most common applications of IMUs are electronic devices (mobile phones, cameras, tablets), gaming and motion control, motion capture, robots, vibration analysis, healthcare monitoring, accessibility interfaces, airplanes, rockets, navigation, personnel/pedestrian tracking, navigation of unmanned aerial/land/water vehicles, automobiles, virtual reality, rehabilitation, positioning and stabilization, education and performing arts, etc.

Inertial systems are useful in the health area for objectively quantifying and assessing human body movement. [1] analyzed the potential of using inertial sensors as a tool to obtain three-dimensional motion data. This allows the evaluation and intervention of human body movement quantifying motor action. They found that IMUs have wide possibilities in health, physiotherapy, physical activity, movement and rehabilitation, training, sports areas, and their combinations.

[2] presented the development of different algorithms that can be used to estimate of the orientation of a quadrotor that is moving three-dimensionally in space. Measurements from different sensors are used to obtain estimates, necessary for vehicle control. Calibration of the different sensors used was performed. They analyzed inertial sensors; their measurements were fused for a more robust estimate. The algorithms were implemented and tested in real time.

[3] used the MPU 6050 inertial sensor with 6 degrees of freedom to determine the surface regularity on unpaved roads. The sensor was mounted on the chassis of a vehicle. A description sheet of the surface damage present at the time of the investigation was obtained. The measurements obtained with inertial sensors detected the surface regularity of the unpaved road on the HV-112 departmental route. This is because the inertial sensors provided data that is more than 90% as the use of precision surveying equipment.

[4] determined that falls are one of the main reasons for mortality worldwide; over time, ways have been sought to provide a better lifestyle to human beings. They developed an embedded signal acquisition system in the *x*, *y*, and *z* axes for three different classes of detections: falls, walking, and immobile. This is possible using the MPU-6050 inertial sensor which sends acceleration signals in all three axes. The signal was processed to extract the characteristics. These characteristics were applied in a Naive Bayes classifier algorithm previously trained with a database.

[5] presented a biomechanics study obtaining the orientation of inertial devices to calculate the rotation angles in the joints of the human body. He analyzed in detail body dynamics, which play an essential role in performance improvement, rehabilitation, and injury prevention. In sports, IMUs are essential in the analysis and optimization in athletes' performance. With the data captured, the technique of a swimmer, runner, cyclist, or basketball player can be evaluated, leading to specific adjustments to their training.

[6] searched for neural network architectures in the literature, to solve the problem of Human Activity Recognition (HAR) with inertial sensors. He implemented some of these architectures and compared the results with those obtained in previous works, using the REALDISP database. He studied the use of acceleration, quaternions, and orientation and how it affects recognition accuracy.

Current smart watches include MEMS-type inertial sensors. These allow the measurement of acceleration and angular velocity that can be used for different motion capture and analysis applications for use in the fields of health and occupational risk prevention, etc. [7] presented several experiences of using this technology, such as determining the type of machine used and the task performed by a worker, the evaluation and monitoring of movement disorders related to neurodegenerative diseases.

[8] develop a new version of the software for managing the MPU-9250 device with the purpose of using it in gait studies in elderly people. Inertial sensors have been highlighted as efficient and appropriate devices due to their various advantages when performing motion tests. They used Python language to make new software for the MPU-9250. This has real-time visualization of signals, reconfiguration in different work modes, access levels, storage, and user interface. The program contains a simple, attractive, robust, reliable, visual, and secure design.

Nowadays, assistive technologies have supported people with disabilities, allowing individuals to get involved in activities where anyone participates. [9] designed an embedded system for the prototype of the evaluation system for orientation and mobility parameters in the rehabilitation of the blind through the application of a mechatronic design. The prototype will be used for the development of validation tests of an orientation and mobility system, with blind patients.

In flights with GPS, the position of the UAV on the ground is obtained directly by the receiver. Since there is no GPS indoors, speed, distance and orientation must be estimated. Inertial systems are the option for sensory fusion with optical flow sensors. [10] analyzed the measurements obtained by the GPS, the readings from the inertial sensors and the optical flow sensor, during autonomous tracking, laying the foundations for a navigation system that fuses sensors and estimates of pose of a quadcopter without GPS.

Due to machine learning, signal processing and IMUs, applications for activity recognition (AR) have been developed. The IMU in the chest is optimal for the AR analysis, posture, cardiopulmonary estimation, voice, swallowing and more. [11] present IMU applications for the chest and summarize the methods, challenges, future directions, etc. They discuss the inertial sensors used, their location on the body and the associated methods depending on the application.

The information obtained by the IMU in a robot is used to determine its position, orientation, and acceleration. [12] compared 42 IMU models from 7 different manufacturers, pointing out characteristics such as structure, connectivity, and communication protocols. They presented useful information quantitatively and qualitatively, providing the user with the possibility to select the appropriate IMU.

Human Activity Recognition (HAR) is a booming area of research, due to the availability of devices such as smart watches, smartphones, and video cameras. The deep learning advancement has allowed HAR to be used in health, sports, and wellness applications. HAR is an assistive technological tool to support the lives of older people by monitoring their physical and cognitive activity. [13] conducted surveys that reveal the role of machine learning in HARs development based on inertial sensors along with environmental and physiological sensors.

The requirement for portable devices to measure respiration increases with various applications such as work, clinics, outdoors, sports, etc. Respiratory rate (RR) is a very important parameter since it indicates possible serious diseases such as pulmonary embolism, pneumonia, emphysema, etc. The methods using inertial meet the requirements of discreet, portability, intelligent, lightweight, and integrable. [14] review innovative wearable devices, sensing strategies, and algorithms that exploit inertial sensors to monitor respiration. They employ various processing tools to extract respiratory parameters from inertial data. It provides useful information for developing wearable sensors to monitor respiratory parameters.

So, this work deals with the evaluation and verification of two Inertial Measurement Units (IMU). A framework for data acquisition and application was implemented through several libraries and programming languages to help other interested researchers. Transformation algorithms are integrated to obtain the orientation of the inertial. Also, these algorithms are contained in libraries that are added to the high-level programming languages (HLL) allowing great graphics capacity.

2. IMUS CHARACTERISTICS

The characteristics of the two IMUs used as examples are described below.

2.1 Sparkfun 9 Degrees of Freedom - Razor IMU

The Razor 9DOF IMU contains three sensors: an ADXL345 (triple-axis accelerometer), ITG-3200 (triple-axis MEMS gyroscope) and HMC5883L (triple-axis magnetometer), 9 degrees of inertial measurement are available. The ATmega328 processes everything. Data is transmitted to a terminal program at 57600 bps. The 9DOF Razor IMU is used as a control element for several applications [15].

2.2 Yost Labs 3-Space Sensor

3-Space contains sensors with various communication methods such as USB, serial, wireless and SPI. The Attitude and Heading Reference System (AHRS) uses a triaxial accelerometer, gyroscope, and a compass sensor along with processing and filtering algorithms in IC for real-time guidance. Measurements are accessed through an open communication protocol, allowing access to data, parameters, and sensor configuration. The data can be consulted in formats such as: rotation matrix, quaternions, Euler angles, axis angle and two vectors. As a USB device it emulates a mouse or joystick. Regarding wireless communication between the IMU and the software, Bluetooth is used. For this, the device is paired with the PC, the communication protocol is configured, the different commands are used and with this the data transfer is carried out [16].

3. REPRESENTING ORIENTATION

A requirement for some technologies is the representation of the position and orientation of objects in their surroundings. The objects can be cameras, robots, drones, tools, etc. Mathematically, in space, a point is described as a vector with coordinates. The vector contains the displacement of the point concerning a reference coordinate system. The Cartesian coordinate system contains orthogonal axes that intersect at the origin. The object orientation is known as pose and is represented with coordinate axes in a specific frame. The rotation matrix **R** defines the transformation of the object's coordinates from a fixed frame to a moving frame, as it rotates (Figure 1). One special property of the $\mathbf{R}_{3x3}$ rotation matrix is orthogonality, since each of its elements contains a unit vector; each element of the matrix represents unit vectors of a fixed frame concerning the mobile one; they have unitary magnitude, and all are orthogonal; its determinant is $|\mathbf{R}|=+1$; Its inverse is equal to the transposed $\mathbf{R}^{-1} = \mathbf{R}^{T}$. The orthogonal rotation matrices for the rotations α, ϕ, θ are those that occur around the x, y, and z axes respectively [17].

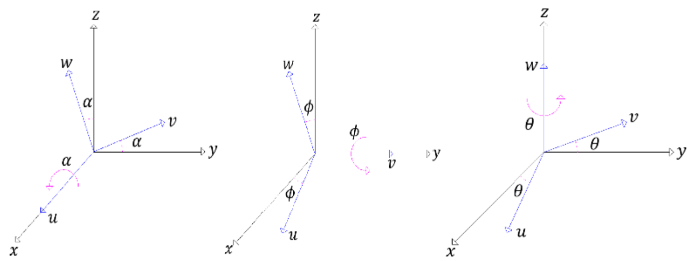

Fig. 1. Rotational matrices respect to α, ϕ, θ angles.

The equations below represent the rotations shown in Figure 1.

$$\boldsymbol{R}(x,\alpha) = \begin{array}{c} \\ x \\ y \\ z \end{array}\!\!\begin{array}{c} \begin{array}{ccc} u & v & w \end{array} \\ \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -sen\,\alpha \\ 0 & sen\,\alpha & \cos\alpha \end{bmatrix} \end{array} \quad \boldsymbol{R}(y,\phi) = \begin{array}{c} \\ x \\ y \\ z \end{array}\!\!\begin{array}{c} \begin{array}{ccc} u & v & w \end{array} \\ \begin{bmatrix} \cos\phi & 0 & sen\,\phi \\ 0 & 1 & 0 \\ -sen\,\phi & 0 & \cos\phi \end{bmatrix} \end{array} \quad \boldsymbol{R}(z,\theta) = \begin{array}{c} \\ x \\ y \\ z \end{array}\!\!\begin{array}{c} \begin{array}{ccc} u & v & w \end{array} \\ \begin{bmatrix} \cos\theta & -sen\,\theta & 0 \\ sen\,\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{array}$$

In a three-dimensional space, the Rotation Matrix defines the orientation of system 0_{uvw} with respect to system 0_{xyz} [17], see Equation (2).

$$\boldsymbol{R} = \begin{array}{c} \\ x \\ y \\ z \end{array}\!\!\begin{array}{c} \begin{array}{ccc} u & v & w \end{array} \\ \begin{bmatrix} i_x i_u & i_x j_v & i_x k_w \\ j_y i_u & j_y j_v & j_y k_w \\ k_z i_u & k_z j_v & k_z k_w \end{bmatrix} \end{array} \tag{2}$$

0_{xyz}	mobile system	$i_x\, j_y\, k_z$	unit vectors
0_{uvw}	Fixed system	$i_u\, j_v\, k_w$	unit vectors

The position $\mathbf{P2}_{xyz}$ of an object with coordinates in the moving reference system 0_{xyz} can be known given the rotation given by the matrix **R** for a known point $\mathbf{P1}_{uvw}$ in the fixed reference system 0_{uvw} [17]. See Equation (3).

$$\begin{bmatrix} \mathrm{P2}_x \\ \mathrm{P2}_y \\ \mathrm{P2}_z \end{bmatrix} = \boldsymbol{R} \begin{bmatrix} \mathrm{P1}_u \\ \mathrm{P1}_v \\ \mathrm{P1}_w \end{bmatrix} \tag{3}$$

4. MATERIALS & LIBRARIES

Next, the materials and software will be described .

4.1 Razor IMU

Figure 2 is a 9 Degrees of Freedom IMU on a single, flat board [15].

Fig. 2. 9 DOF Razor IMU.

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Communication can be done employing serial terminals TX and RX pins between IMU → Arduino → PC. See Table 1.

Table. 1 Razor IMU connection to Arduino Due.

9DOF Razor IMU	Arduino Due (Serial1)
TX0	RX1
RX1	TX1
3.3V	3V3
GND	GND
ArduinoDue (Serial) → USB → Computer	

4.2 3-Space mini Bluetooth

Figure 3 is a miniature, wireless, dual mode Bluetooth/LE Inertial Measurement Unit (IMU) + Attitude & Heading Reference Systems (AHRS). Its features are accessible via an open communication protocol that allows access to all sensor data and configuration parameters [16].

Fig. 3. 3-Space mini Bluetooth.

4.3 3-Space Orientation Commands

Commands identified by codes are sent to access different data contained in the 3-Space. The 3-space responds with a series of bytes to the sent code. To understand these values, the information in Table 2 is necessary. For example, sending command 2 produces a 36-byte string response corresponding to 9 floating numbers, this is the $\mathbf{R}_{3x3}$ Rotation matrix [18], see also Figure 4 (left). Other commands to obtain the orientation of the sensor are 0→Quaternions and 1→Euler Angles.

Table. 2 Commands for 3-Space.

Command	Description	Long Description	Return Data Len	Return Data Details
0	Get tared orientation as Quaternion	Returns the filtered, tared orientation estimate in Quaternion form	16	Quaternion (float x4)
1	Get tared orientation as Euler angles	Returns the filtered, tared orientation estimate in Euler Angle form	12	Euler Angles (float x3)
2	Get tared orientation as Rotation Matrix	Returns the filtered, tared orientation estimate in Rotation Matrix form	36	Rotation Matrix (float x9)
96	Tare with current orientation	Sets the Tare orientation to be the same as the current filtered orientation.	0	
230	Get Hardware Version string	Returns a string indicating the current Hardware Version.	32	Hardware Version (string)

4.3 Software

The Terminal view of the 3-Space Sensor Software Suite is shown in Figure 4 (left). In this case the software is connected to the sensor via Bluetooth through the COM6 serial port. Commands have been sent to read the hardware version of the inertial and the reading of the Rotation Matrix **R** (white text). The sensor responds with green text. Figure 4 (right) shows the visual interface of the inertial sensor with its system with its XYZ orthogonal reference axes [18].

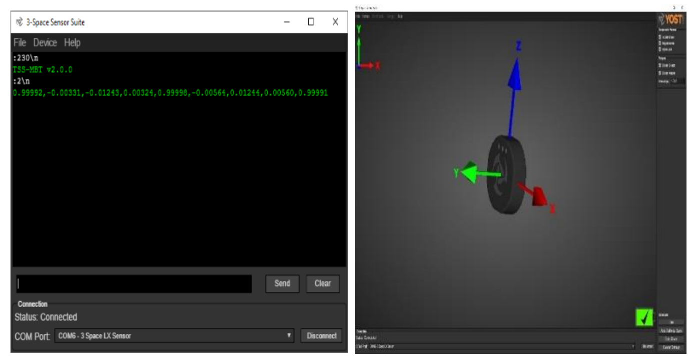

Fig. 4 3-Space Sensor Suite Terminal & virtual view.

4.4 Libraries

Peter Corke's Toolbox (Figure 6) contains many useful functions for the study and simulation of position, orientation, movement, kinematics, dynamics, trajectories, etc. The tool contains functions and classes to represent orientation and pose in 2D and 3D with objects of type SO(2), SE(2), SO(3), SE(3) containing matrices, quaternions, spins, triple angles, etc. The tool provides functions to convert and manipulate data types, such as vectors, unit quaternions, and homogeneous transformations that are necessary to represent three-dimensional orientation and position [19]. Another library is the Tucker McClure one [20].

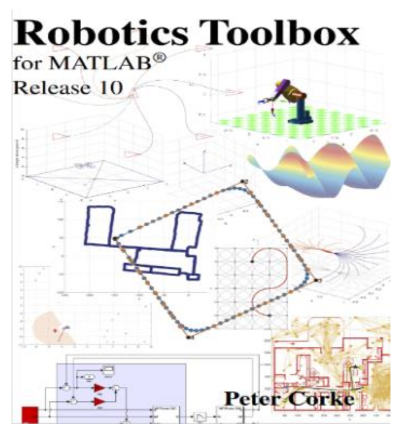

Fig. 6 Peter Corke's toolbox.

5. RESULTS

The results obtained from the two IMUs used as examples are described below.

5.1 Razor IMU

Regarding the inertial Razor IMU, it was connected to the Arduino Due, both work with 3.3V logic levels. The inertial transfers serially its perpendicular Roll, Pitch, Yaw (RPY) angles to the Arduino Due at a transmission rate of 57600 bps. The Due then relays the RPY to the serial monitor of the Arduino IDE software, see Figure 7.

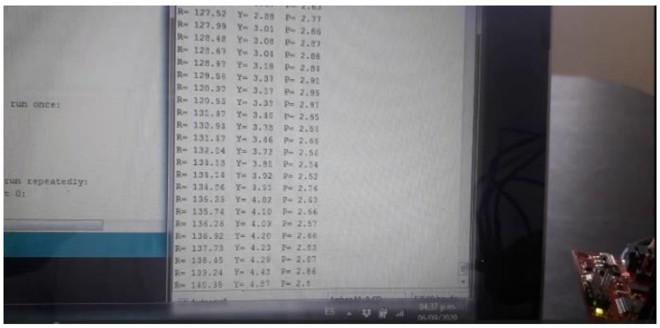

Fig. 7 Data returned by the Razor IMU .

5.2 3-Space mini Bluetooth

Now, talking about the 3-Space inertial sensor, being it a wireless Bluetooth device, it must be registered within the PC operating system. This is done in the Windows Devices Box Dialog. A Bluetooth device should be added with the name YostLabsMBT, it must be paired with the sensor using its corresponding password (Figure 8).

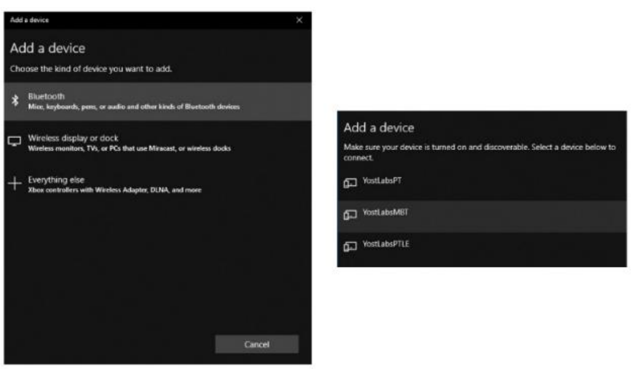

Fig. 8 Name of 3-Space into Bluetooth Device Manager.

As an example of the use of the reference systems and rotation matrix, **R**, consider that a point located at $\mathbf{P1}_{uvw}$ = [4,8,12] referenced in the moving system 0_{xyz}, is rotated θ = -90° with respect to the 0_w axis of the fixed reference system, 0_{uvw}, see Eq (3). The $\mathbf{P2}_{xyz}$ coordinates can be determined through the rotation matrix **R**.

$$\boldsymbol{R}(z,\theta)=\begin{bmatrix}\cos(-90°) & -sen(-90°) & 0\\ sen(-90°) & \cos(-90°) & 0\\ 0 & 0 & 1\end{bmatrix}=\begin{bmatrix}0 & 1 & 0\\ -1 & 0 & 0\\ 0 & 0 & 1\end{bmatrix}$$

$$\begin{bmatrix}P2_x\\ P2_y\\ P2_z\end{bmatrix}=\begin{bmatrix}0 & 1 & 0\\ -1 & 0 & 0\\ 0 & 0 & 1\end{bmatrix}.\begin{bmatrix}4\\ 8\\ 12\end{bmatrix}=\begin{bmatrix}8\\ -4\\ 12\end{bmatrix} \tag{4}$$

The location of the point after rotation is $\mathbf{P2}_{xyz}$=[8,-4,12] Eq (4).

In Figure 9 the location of point $\mathbf{P1}_{uvw}$ in the fixed reference system 0_{uvw} is seen in black. In red is the point $\mathbf{P2}_{xyz}$ in the 0_{xyz} reference system.

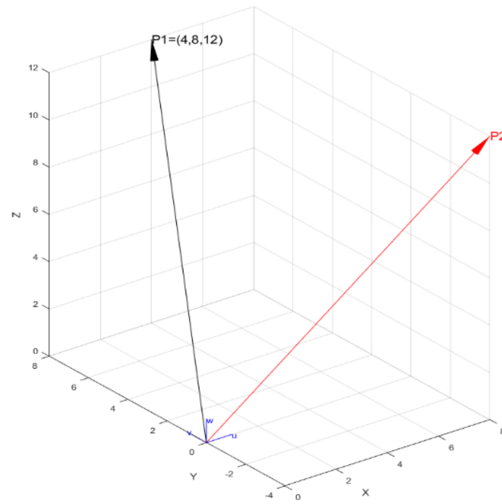

Fig. 9 Vector **P1** *is rotated θ= -90° to reach position* **P2**.

Now, this rotation **R** can be directly obtained from the inertial sensor, through the respective command using Matlab.

Next, the explanation is included in the format of `%Matlab comments`

```
% Open the serial port
s = serial("COM6");
% Open COM6
fopen(s);


% Read Movil system Oxyz after it was rotated
% manually by approximately θ≈-90°
% Read orientation as a Rotation Matrix from COM6
fwrite(s,':2\n','char');
R = fgets(s)
```

$$\boldsymbol{R}=\begin{bmatrix}0.0560 & 0.8751 & -0.4807\\ -0.9976 & 0.0294 & -0.0626\\ -0.0407 & 0.4840 & 0.8747\end{bmatrix}$$

```
% Read orientation as Quaternion from COM6
fwrite(s,':0\n','char');
Q = fgets(s)

% The 3 first elements V is a unit vector
% The last element s, is a scalar that
% contains the rotation θ
```

```
% Q = cos (theta/2) < v sin(theta/2)>
%              V                  S
%    ------------------------   ------
Q = [0.19528,-0.15664,-0.66888,0.69995]

% Read orientation as Euler angles from COM6
fwrite(s,':1\n','char');
E = fgets(s)
E = [0.06478,-0.50225,-1.54202]

% Using Matlab, we can transform from Quaternion to
% Rotation Matrix
quat2rotm([Q(4) Q(1:3)])
```

$$\begin{bmatrix} 0.0560 & 0.8751 & -0.4807 \\ -0.9976 & 0.0294 & -0.0626 \\ -0.0407 & 0.4840 & 0.8747 \end{bmatrix}$$

```
% Using Tucker Mcclure we can transform from Euler to
% Quaternion
ea2q(E',[1 2 3])'
[0.1956   -0.1563   -0.6804    0.6887]
% And Tucker Mcclure goes from Quaternion to Euler
% angles too
q2ea(Q, [1 2 3])'
[0.0728   -0.5012   -1.5068]

% Using Peter Corke´s Toolbox also we can transform
% from rotation matrix R to Quaternion
UnitQuaternion(R)
0.7 < 0.19489, -0.15714, -0.66883 >

% Now,define position of original vector P1 as
% explained earlier
P1=[4,8,12];

% Getting P2 from original position P1 after it was
% rotated by R, gotten from 3-Space mini Bluetooth
P2=(R*P1')'= [1.4564   -4.5072   14.1974]
```

Figure 10 shows the original position of vector **P1**, and the position of vector **P2** after **P1** was Rotated by **R**. **R** was gotten from the 3-Space inertial sensor after a rotation of $\theta \approx$ -90°.

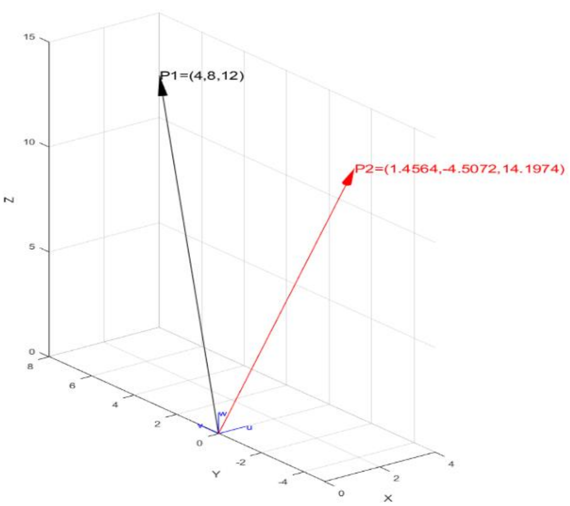

Fig. 10 Position of vectors **P1** *and* **P2** *from a rotation approximately $\theta \approx$ -90° from the 3-Space.*

6. CONCLUSIONS

A framework was implemented for the data acquisition and use provided by two inertials. The inertials were used to compare them, clearly the 3-Space sensor is superior as it is more modern, is wireless and contains a whole set of commands to work with it, while the Razor is older and provides only a single form of operation. Various libraries and programming languages were used. Transformation algorithms that obtain inertial orientation were integrated. The algorithms are contained in libraries. They are added to high-level programming languages (HLL). In addition, HLL offers great graphic capacity, improving the framework.

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