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Design and validation of biomechanical sensors for the surgical, orthopedic and rehabilitation fields

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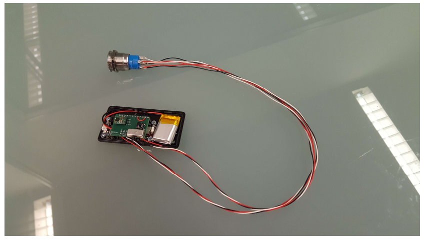
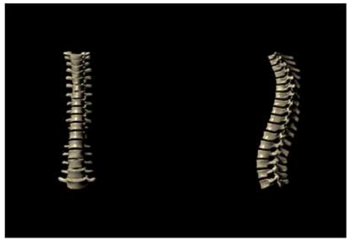
The work is focused on the development and improvement of three biomechanical-related devices, making them more reliable, easier to use, with software, structural and ergonomic modifications, where necessary.

1. A sensor of angular orientation

2. A wireless device communicating with a KAFO



3. An application for the visualization of a human spine



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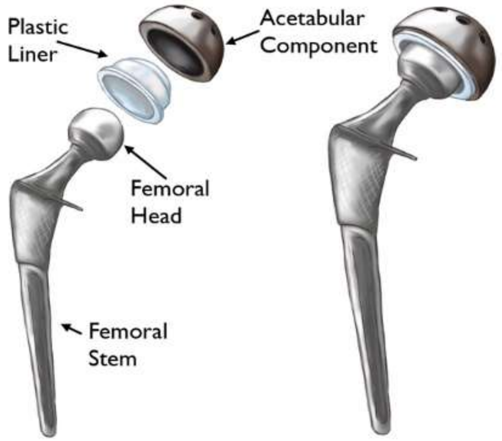
First project: background

- The new device will substitue a tool used by the surgeon during the hip's subsitution surgery
- The old tool had low accuracy and the othosis could be bad placed (this involves hip dislocation and a wear of the implant, that drives to a new operation in less than 10 years)
- The device developed will use an IMU (3-axes accelerometer, 3-axes gyroscope and 3-axes magnetometer) and LEDs that will guide the surgeon during the operation to the correct angulation.



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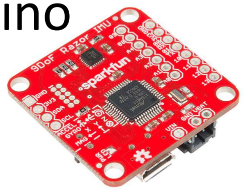
First project: development

The actual device is using a SparkFun Razor M0 IMU programmed with Arduino



- The magnetometer of the sensor needs a calibration on-field
- The LEDs need to be brighter (in the surgery room there is a powerful light) and be placed to the side of the device, in order to face the surgeon
- Add some parts at the device so it can be fixed at the bar with zip ties
- Compare several sensor fusion algorithms in order to use the most accurate

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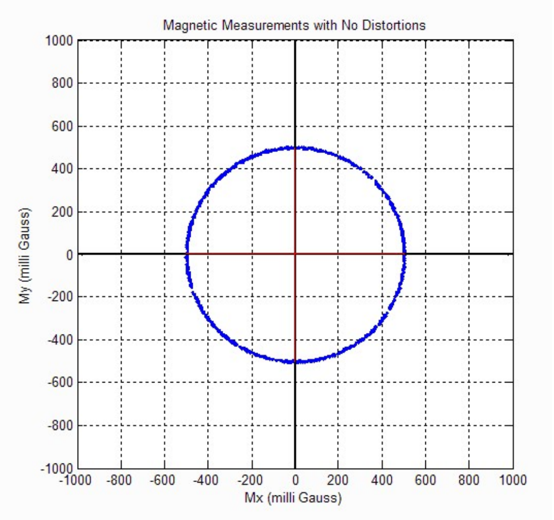
Calibration of the magnetometer - 1

The magnetometer of the IMU needs a calibration, because the magnetic field is variable in each place:

The ideal magnetic field can be represented as a sphere. Sectioning the sphere with a plane passing through the origin, is obtained a circumference.



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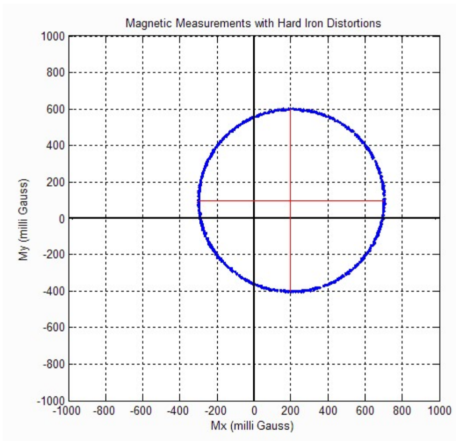
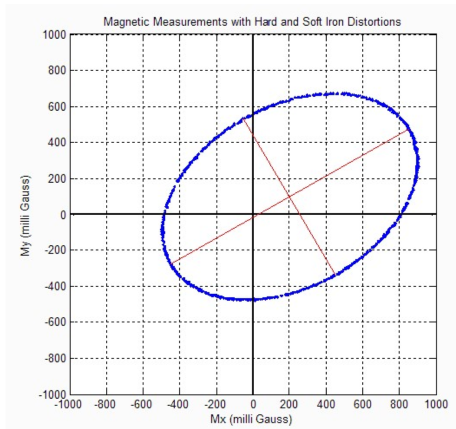
Calibration of the magnetometer - 2

Actually, there are two effects that affect the sphere making it an ellipsoid:

- Hard-iron distortion: is created by objects that produce magnetic field (e.g. a piece of magnetized iron)

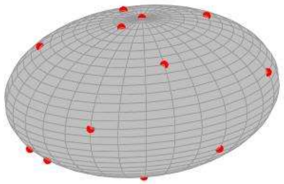


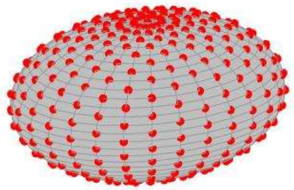
- Soft-iron distortion: is given by objects that distorts the magnetic field in the nearby (e.g.: nickel and iron)



Calibration of the magnetometer - 3

The first thing to do is to record a number of points (x, y, z in [Gauss]) with the magnetometer. With the calibration by PC, the number of points colud be any; instead with the calibration implemented in the device, there is a limited memory.





The points have been chosen with a distance criterium, in order to fit all the ellipsoid and to be equally spaced.

All the calibration process was programmed with Arduino: the data storing, the calculation of the parameters of the fitted ellipsoid, the calculation of the eigenvalues and eigenvectors and finally the correction matrix for the magnetometer.

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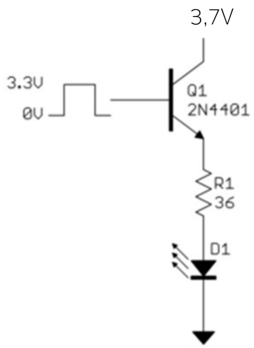
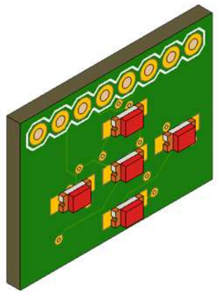
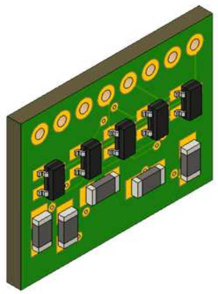
LEDs - 1

The current LEDs mounted on the device are on the top of it and this make them difficult to be seen, moreover the light is not enough to be clearly seen. The PCB that carried all the electrical circuit was redsigned from the beginning. This circuit guarantees a constant current in LEDs independent of the battery voltage.







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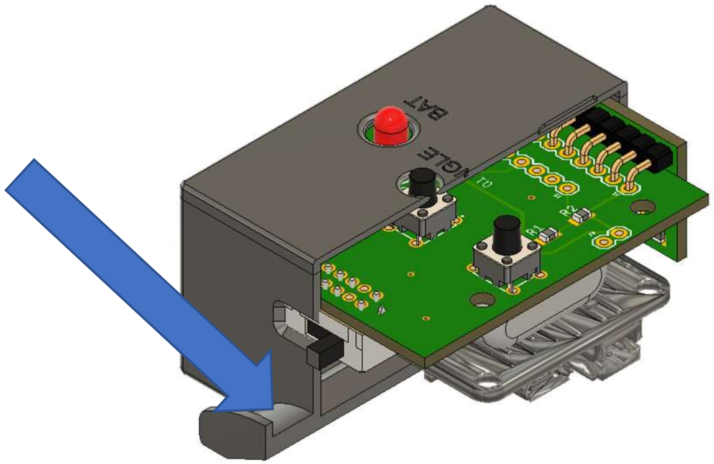
Parts for secure the device - 2

The device needed a way to be fixed at the rod. Since the case is built with Additive Manufacturing technique, is possible to design any shape for the extremities.



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Estimation and comparison - 1

The previously existing device has implemented a Madgwick's algorithm for sensor fusion. It has been compared with other two Kalman's filters for seeking the best estimator of the angulation. Every filter used a quaternion for identify the spacial rotation.

Each filter was benchmarked with a set of data recorded using a motion tracking system that involves infrared cameras (that are way more accurate). The error was calculated as the minimum rotation angle between the tracking system estimation and the filter estimation. An optimization was performed to find the parameters of each filter that minimized the error with respect to the camera result.

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Estimation and comparison - 2

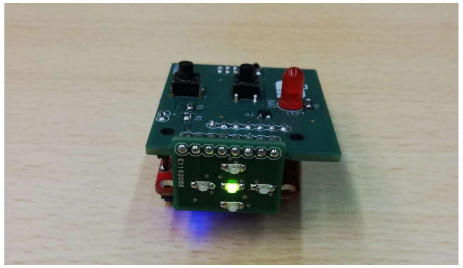
1. Madgwick's filter: was the most accurate algorithm, with a mean error of 1,7185°.

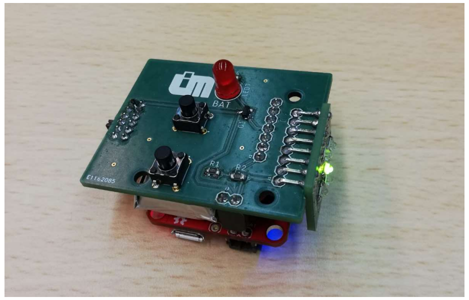
2. Kalman's filter: the first Kalman filter was designed using the gyro data as input. The mean error is 3,172533°.

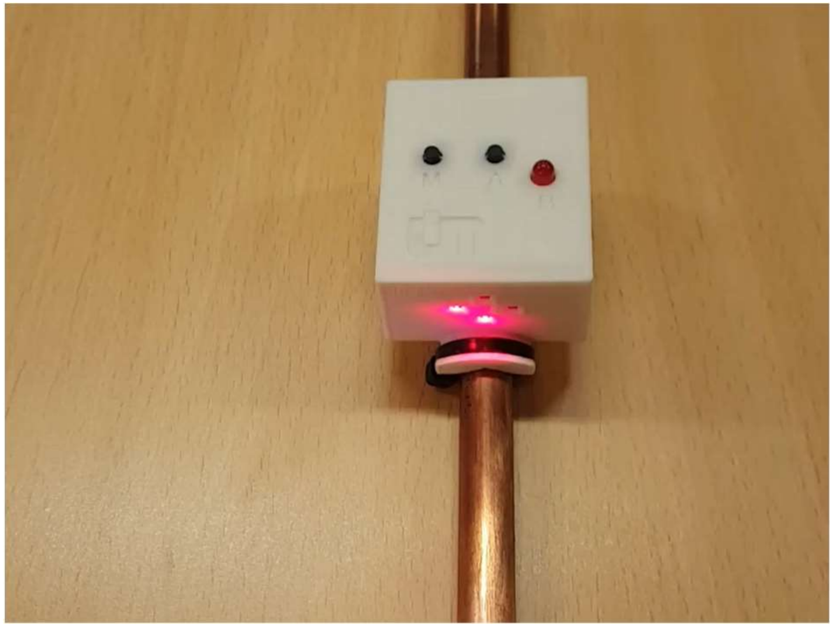
3. Kalman's filter: the second Kalman filter was designed using the gyro data as sensor. The mean error is 3,420788°.

First project: final prototype

The final prototype will assure a correct orientation of the implant and a small operation time.







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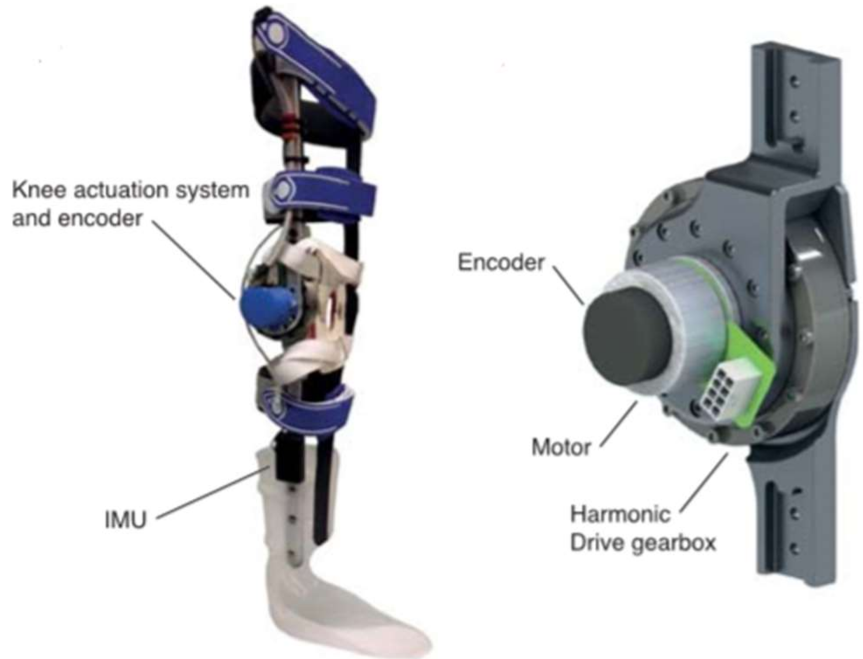
Second project: background

The LIM, in association with other universities (UPC and UEX), worked on an active KAFO used by people that had a Spinal Cord Injury.

The device required for this project was a system that allows the patient to control the orthosis, so he can walk, stand or just turn off the KAFO when he wants. It will use a Bluetooth Low Energy communication for sending the commands to the orthosis. A PC or smartphone application was used for this, which prevented autonomous use.



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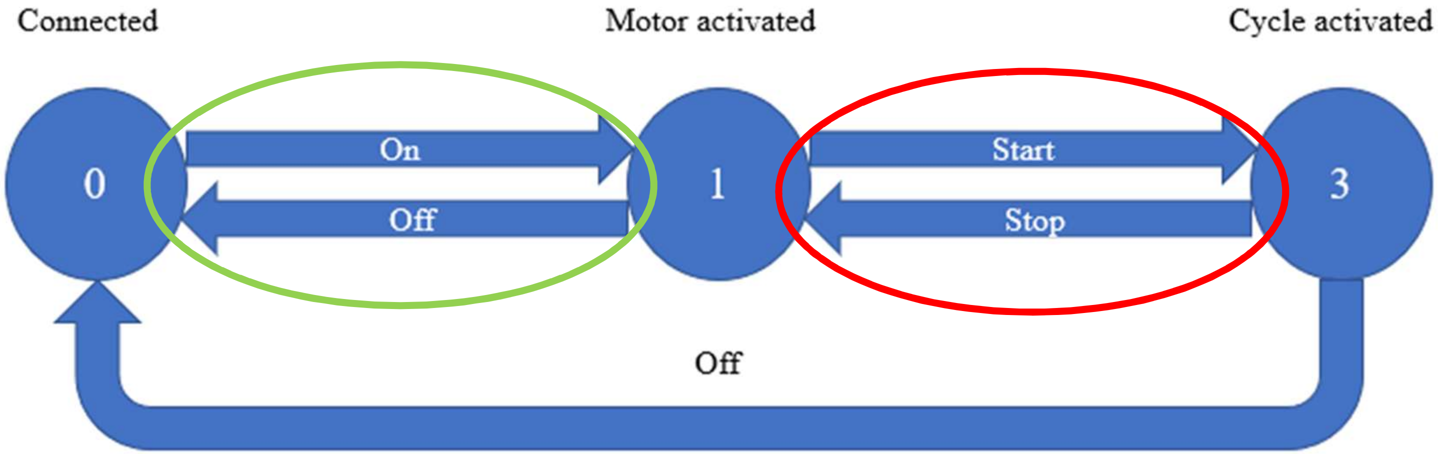
Second project: development

The device developed used an Adafruit Feather 32u4 Bluefruit LE programmed with Arduino. The code controlling the orthosis is running in a BeagleBone Black, which is an embedded Linux system. Was added a part of Bluetooth communication at the Qt Application running in it.



The device has two push button for sending two different commands and they are physically different and placed in different sites.

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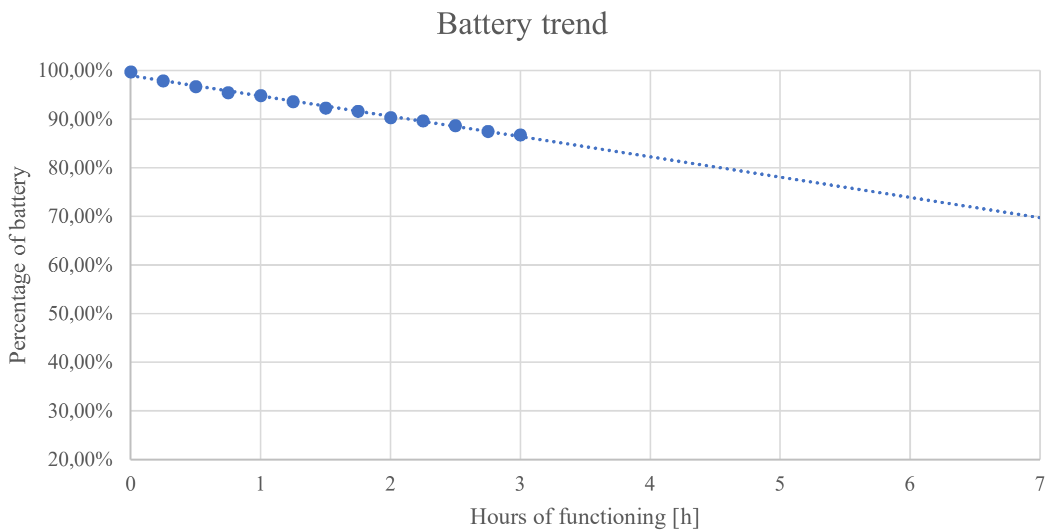
The Bluetooth Low Energy has a very low power consumption. For monitoring the discharge of the battery was tested the system with a continuous use of the Bluetooth antenna.



Hours	Batt.
0,00	99,68%
0,25	97,88%
0,50	96,66%
0,75	95,44%
1,00	94,83%
1,25	93,57%
1,50	92,28%
1,75	91,63%
2,00	90,30%
2,25	89,61%
2,50	88,67%
2,75	87,49%
3,00	86,76%

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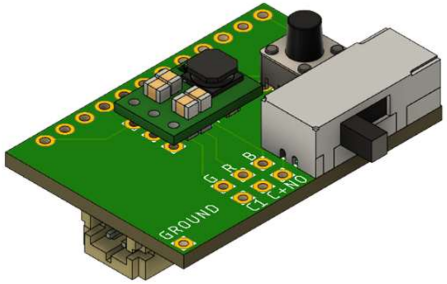
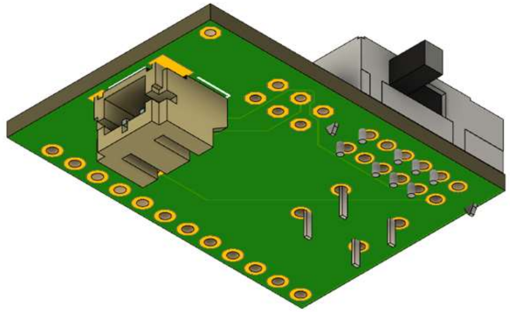
The device needs a PCB that carries The connection for the buttons, the voltage regulator (for regulate the voltage used by the LEDs of the pushbutton in the handle) and a JST connector.





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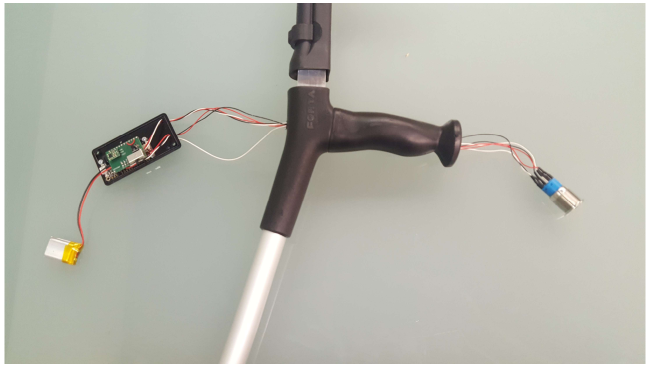
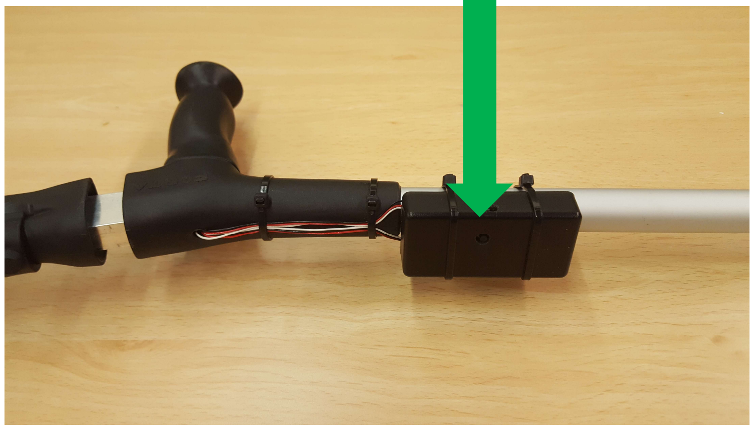
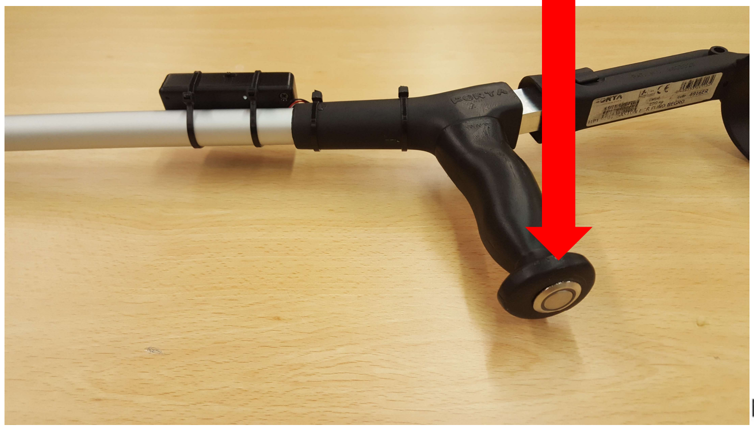
Second project: final protype



Button in the case, used for turning on or off the motor. It has been placed here for not pushing it accidentally



Button in the handle, it has incorporated some LEDs for a visual check of the status of the orthosis



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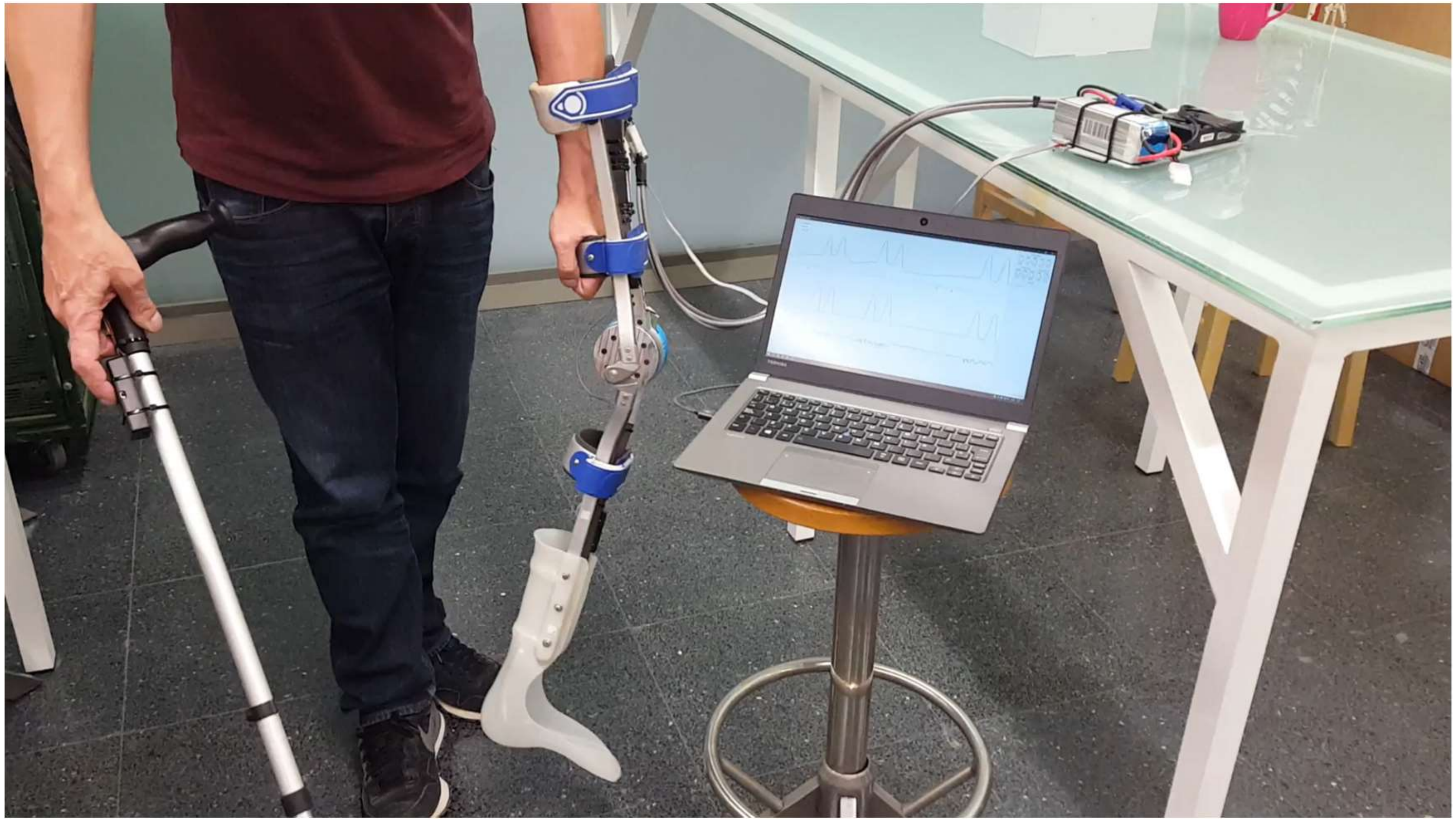

Third project: background

The third and last project was focused on the development of an application that, with the use of 3 IMUs, will visualize the displacements and the rotations of the human spine. This was asked to the LIM by a company to study ergonomics in workplaces, evaluating the bending of the column that occurs in them.

There is currently a similar application using an acquisition system based on tracking markers with infrared cameras. This current methodology requires measurements with the use in the camera capture room. With the new application, using inertial sensors, laboratory testing can be avoided.

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Third project: development

Starting from a 3D model of a 17 vertebrae spine, was created a multibody model. The position and orientation of each vertebra is obtained from a recursive relationship, which depends on the orientation angles of all the vertebrae.

The model follows the relationship $\mathrm{r}_i = \mathrm{r}_{i-1} + \mathrm{A}_{i-1}\bar{\mathrm{r}}_i$

Where

$$\mathrm{r}_i = \begin{bmatrix} \mathrm{x}_i \\ \mathrm{y}_i \\ \mathrm{z}_i \end{bmatrix}$$

Is the origin of each vertebra, and that the first is at the origin of coordinates

$$\bar{\mathrm{r}}_i = \begin{bmatrix} \bar{\mathrm{x}}_i \\ \bar{\mathrm{y}}_i \\ \bar{\mathrm{z}}_i \end{bmatrix} = \begin{bmatrix} x_i^0 \\ y_i^0 \\ z_i^0 \end{bmatrix} - \begin{bmatrix} x_{i-1}^0 \\ y_{i-1}^0 \\ z_{i-1}^0 \end{bmatrix}$$

Is the vector of relative coordinates of each vertebra in the undeformed position

And the rotation matrix

$$\mathrm{A}_i = \mathrm{R}_\mathrm{z}(\alpha_i)\mathrm{R}_\mathrm{y}(\beta_i)\mathrm{R}_\mathrm{x}(\gamma_i)$$

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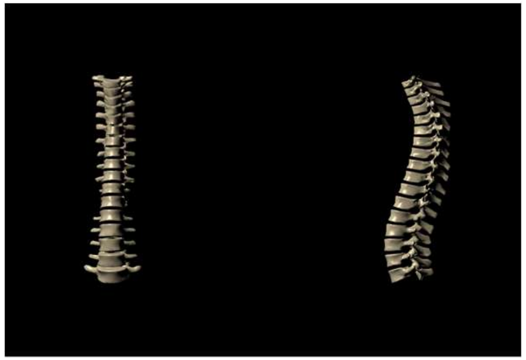
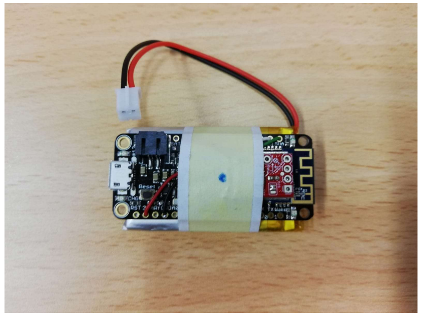
The application creates two views of the spinal cord to highlight the movementes in two different planes.



The sensors used for acquiring the data were formed by an Adafruit Feather M0 WiFi with IMUs MPU9250 soldered on it and it is programmed with Arduino.



Three sensors are placed along the spine of the user and send data (quaternion of the rotation) at the PC, where is running a Qt application.

The application uses the data and creates a spline that interpoles the quaternions, which are used for calculate and visualize the movements of the vertebrae.

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Third project: final prototype

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Conclusions

Almost all the prorotypes have been implemented with success

1. Now is possible to assure to the doctor that the device is more accurate than the old system, because the range of the angles is very tight and reach an accuracy that is quite difficult to get with only the visual feedback
2. With this new device and new turning on/off procedure, the user will be able to activate and deactivate the KAFO easily and safely in a more practical way. Thanks to the multicolour LED in the handle, the user will know if the orthosis is receiving or not receiving the commands
3. The new application permit to unlink from the laboratory capture room and make the evaluation of the movements on real users doing the real movements

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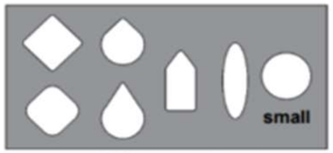
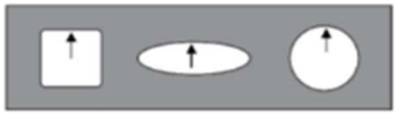
Future work

All the prototypes need some future work fo be improved

1. The next steps will be the industrialization of the boards and the case, which could need some revisions:
    1. Top of the case: it can be possible replace the screws with some snap fits to make faster the assembling process and reduce the assembly time and the number of components (DFA techniques).
    2. Case:
        1. It is possible to close the hole that now permits the upload of the code through the mini-USB port → with the final version, the device will need only the port for recharging
        2. If the manufacturing technology will remain an additive manufacturing, the holes on the vertical walls should be rethought in a way that they self-sustain.



Self-supporting



Support is required

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Future work

2. Redesign the whole system to make a commercial version. Right now this is being carried out by an UPC spin-off company (ABLE Human Motion).

3. The new system should be compared with the old and evaluate the accuracy of it. Should be determined the optimal number of IMUs in order to enhance the accuracy.

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Thank you for your attention

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Calibration process

Ellipsoid equation:

$$Ax^2 + By^2 + Cz^2 + 2Dxy + 2Exz + 2Fyz + 2Gx + 2Hy + 2Iz + J = 0$$

The parameters are stored in a K matrix

$$K = \begin{bmatrix} A & D & E & G \\ D & B & F & H \\ E & F & C & I \\ G & H & I & J \end{bmatrix}$$

So the equation ca be rewritten

$$\vec{r}^{T} K \vec{r} = 0$$

Where

$$\vec{r} = [x \quad y \quad z \quad 1]$$

K contains the translation of the center, the scaling of the axes (for these scalars there is an ellipsoid it is not a sphere) and the rotation of the reference system.

Calibration process

The center can be calculated as

$$\overrightarrow{\mathrm{center}} = -\mathrm{K}(1{:}\,3,1{:}\,3)^{-1}\mathrm{K}(1{:}\,3,4) = [\mathrm{x}_c \quad \mathrm{y}_c \quad \mathrm{z}_c]$$

The scaling effect depends by the eigenvalues of a R matrix

$$\mathrm{R} = \mathrm{TKT}^{T}$$

Where

$$\mathrm{T} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \mathrm{x}_c & \mathrm{y}_c & \mathrm{z}_c & 1 \end{bmatrix}$$

The characteristic polynomial of the R-matrix is

$$\lambda^3 + \mathrm{l}\lambda^2 + \mathrm{m}\lambda + \mathrm{n} = 0$$

Calibration process

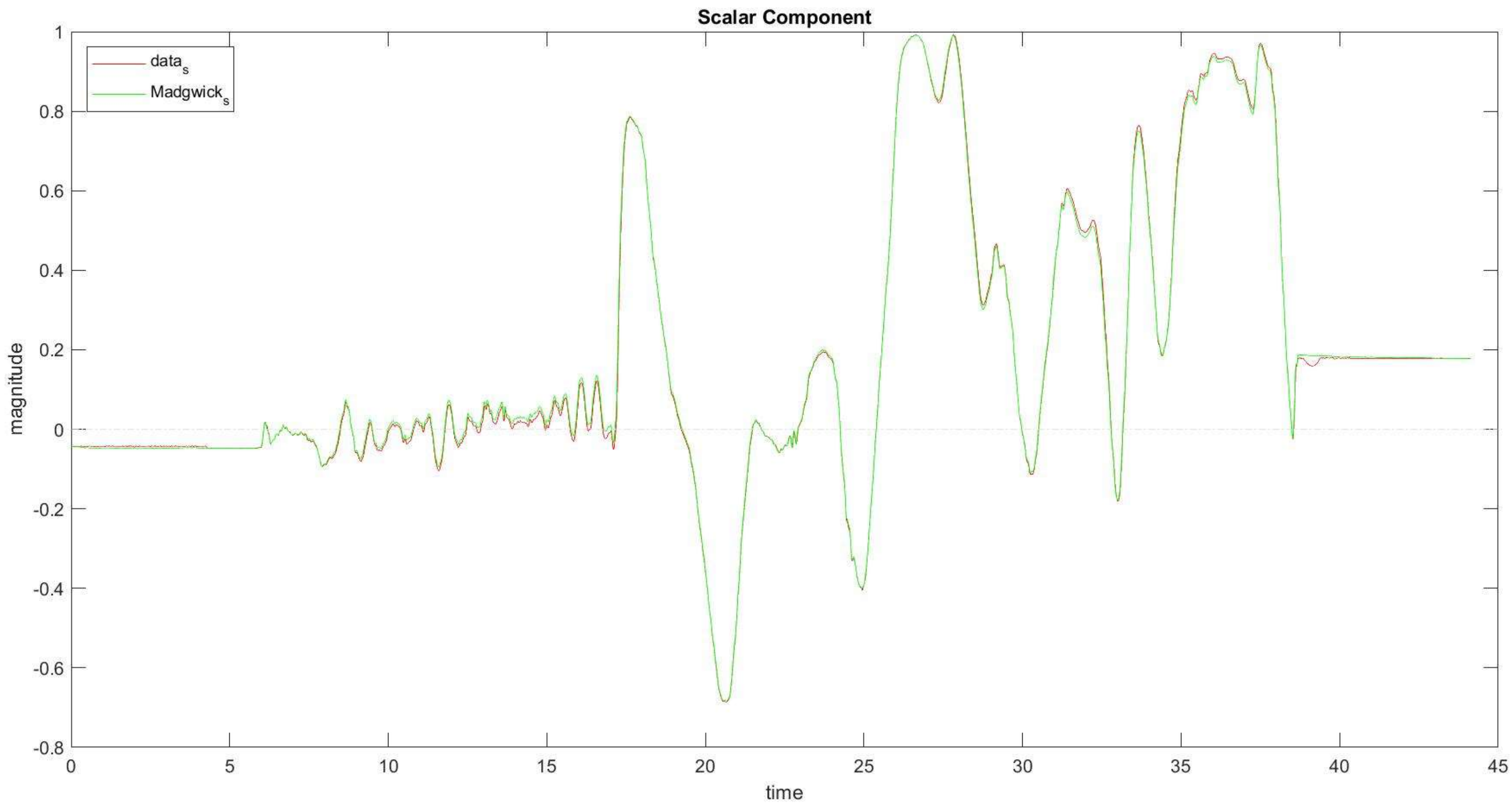
In order to avoid iterative methods, it is possible to solve the third grade equation with the Vieta's method where l, m and n parameters are

$$\mathrm{l} = -\big(\mathrm{R}(1,1) + \mathrm{R}(2,2) + \mathrm{R}(3,3)\big);$$
$$\mathrm{m} = \mathrm{R}(1,1)\mathrm{R}(2,2) + \mathrm{R}(1,1)\mathrm{R}(3,3) + \mathrm{R}(2,2)\mathrm{R}(3,3) - \mathrm{R}^2(1,2) - \mathrm{R}^2(1,3) - \mathrm{R}^2(2,3);$$
$$\mathrm{n} = \mathrm{R}(1,1)\mathrm{R}^2(2,3) + \mathrm{R}(2,2)\mathrm{R}^2(1,3) + \mathrm{R}(3,3)\mathrm{R}^2(1,2) - \mathrm{R}(1,1)\mathrm{R}(2,2)\mathrm{R}(3,3) - 2\mathrm{R}(1,2)\mathrm{R}(1,3)\mathrm{R}(2,3);$$

The rotation is calculated as the normalized matrix of the eigenvectors.

The calibration can be done right before the surgery, by pushing a button and will last a few seconds.

Madgwick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Madgwick_s
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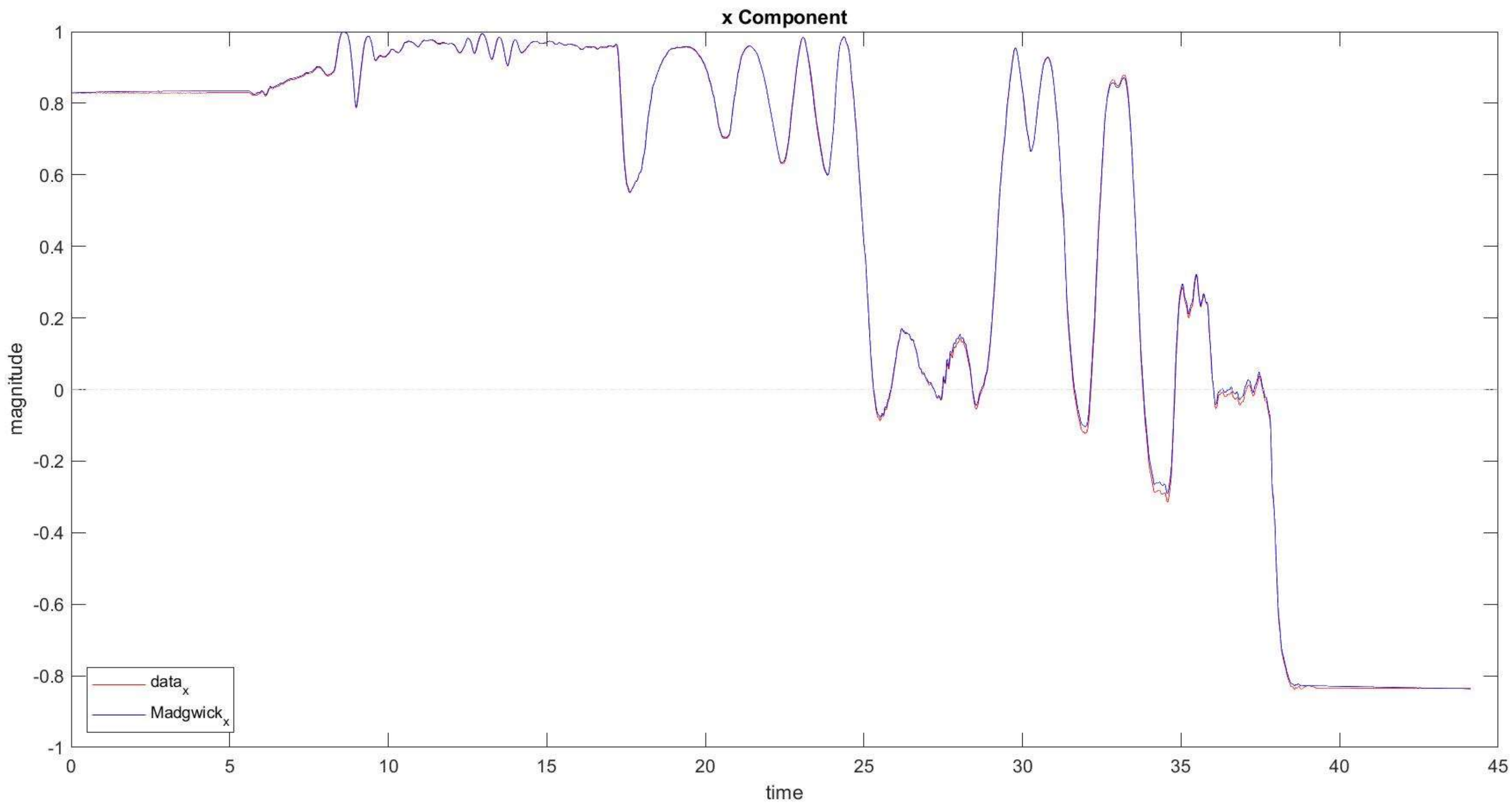
Madgwick



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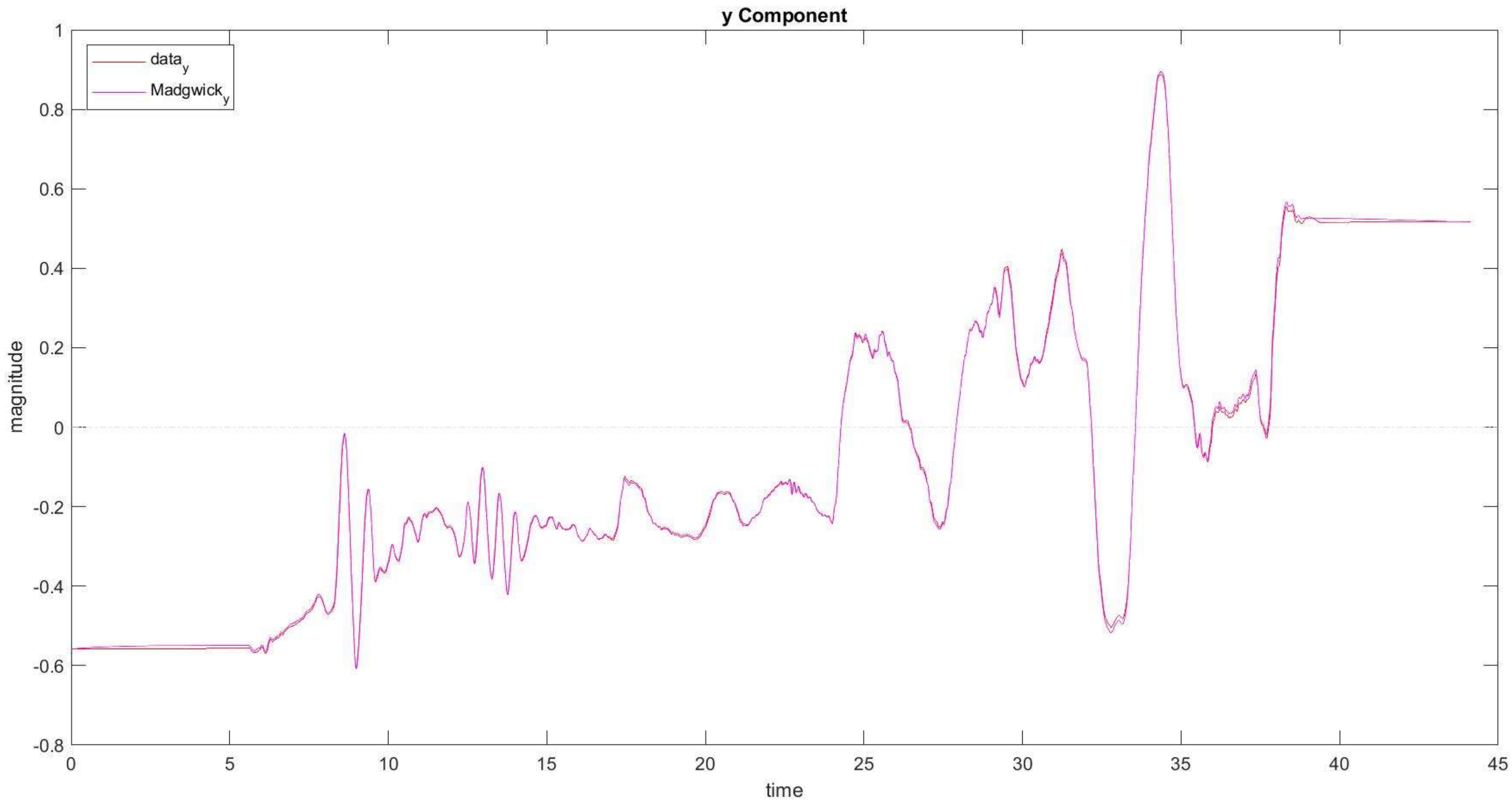
Madgwick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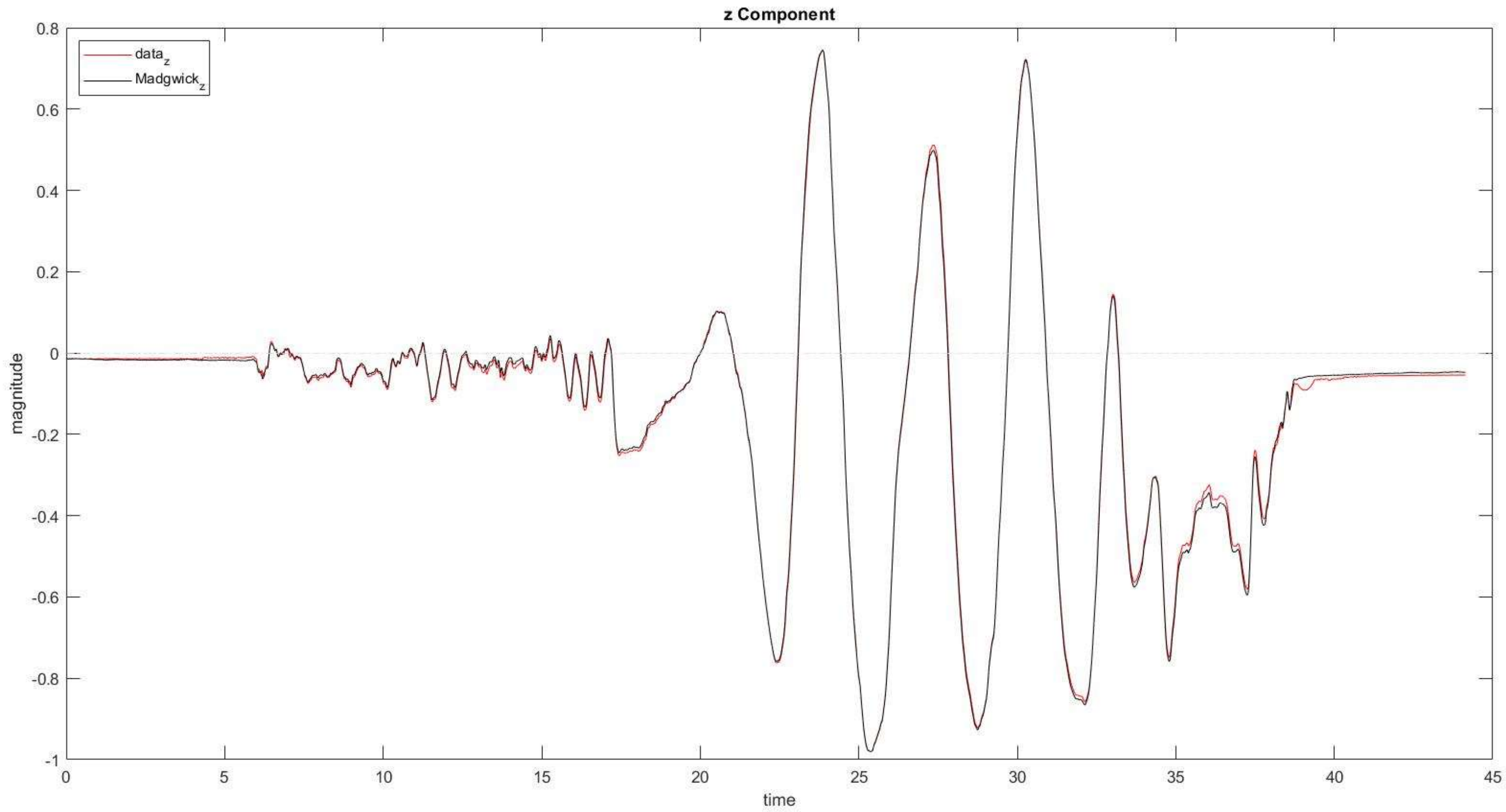
Madgwick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$Madgwick_z$
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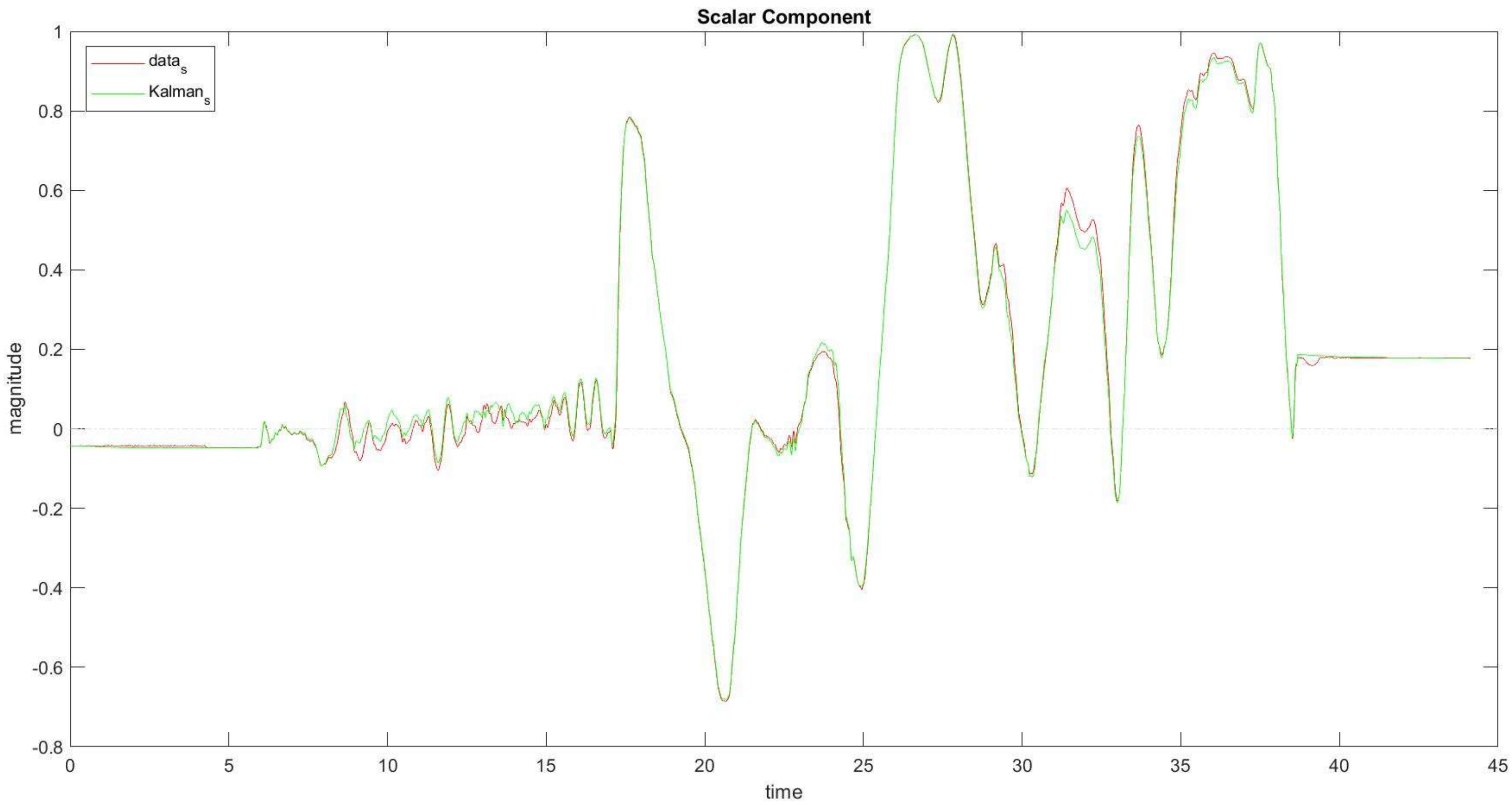
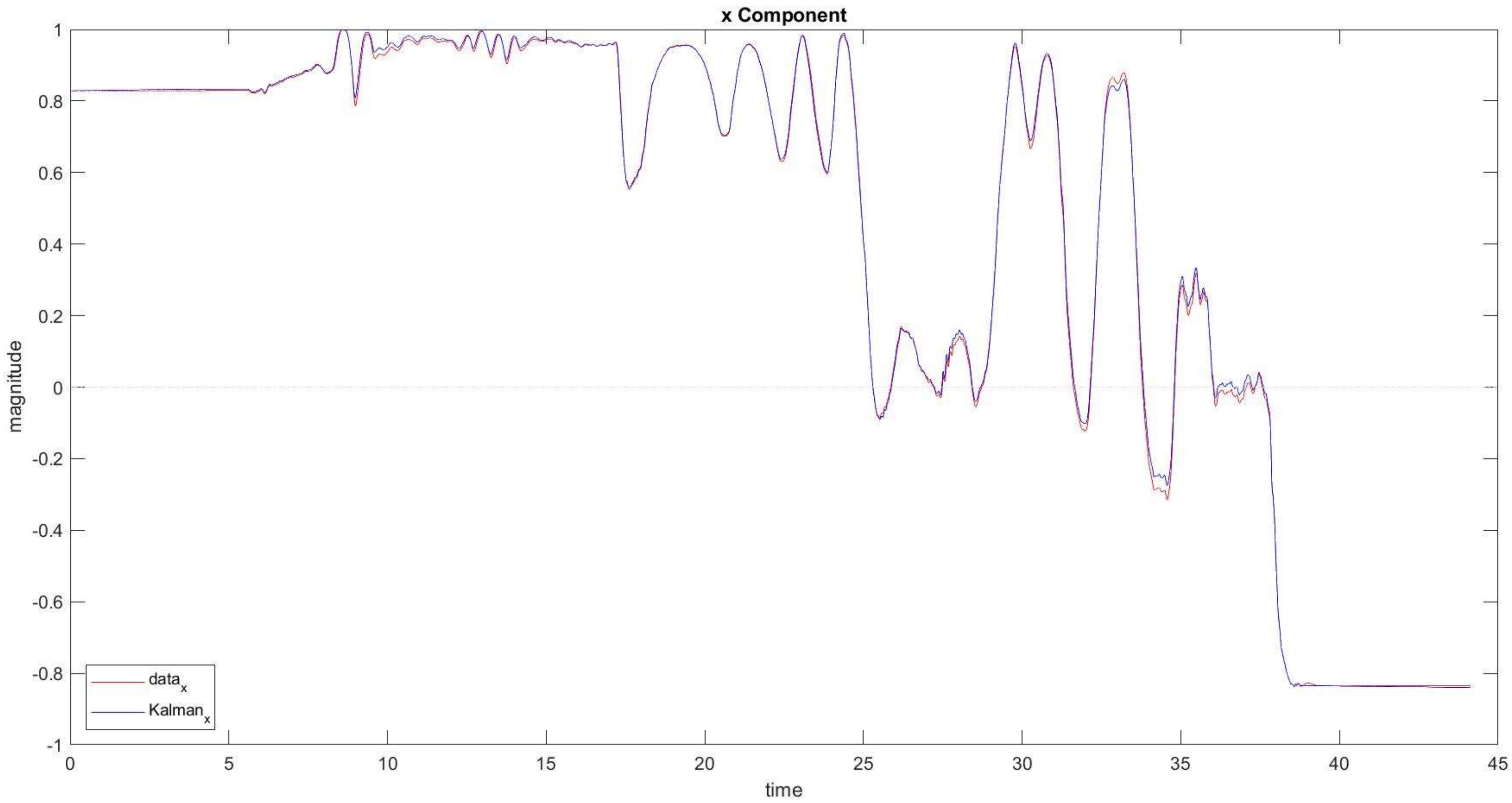
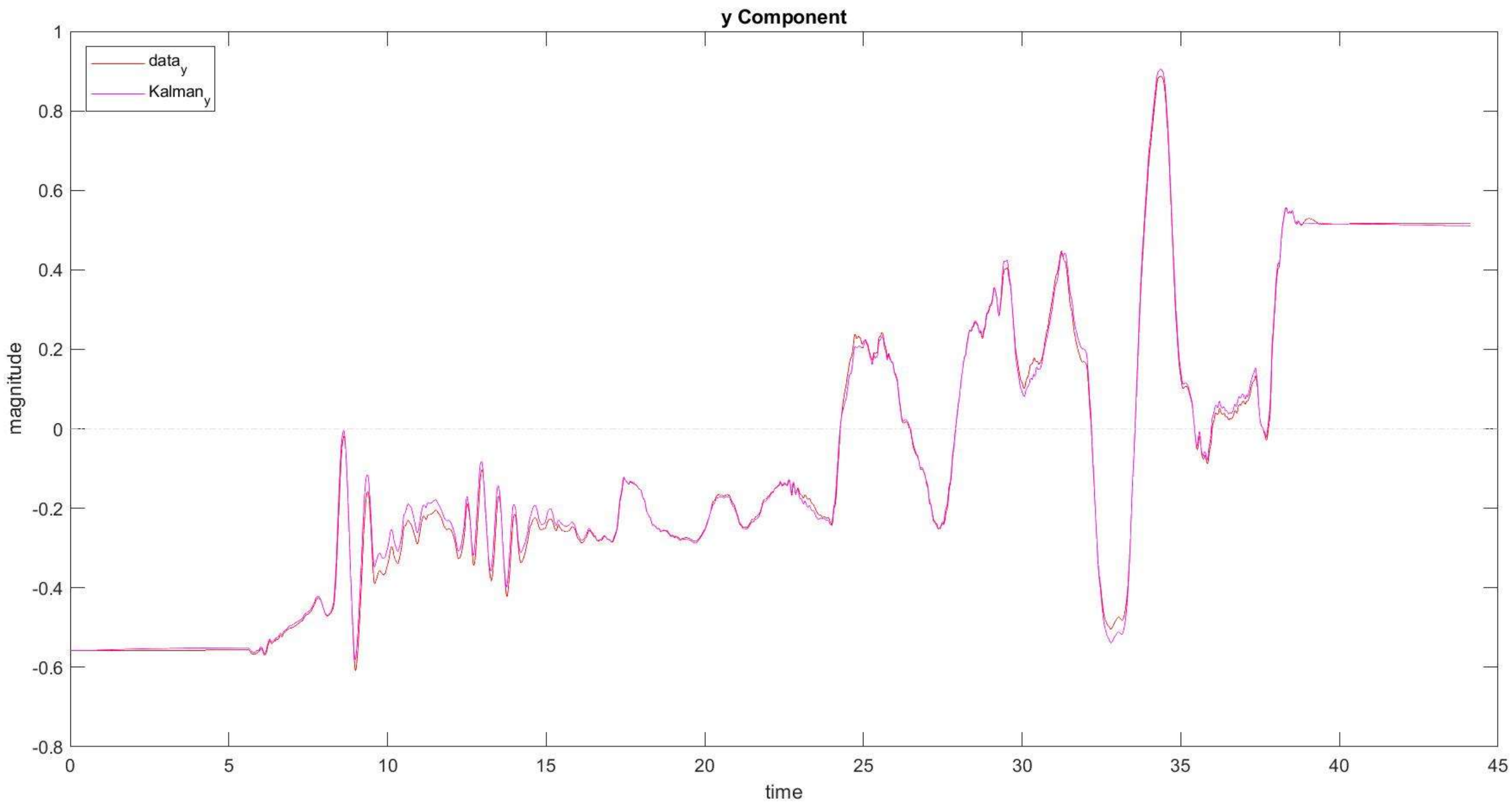
Kalman’s filter: gyro as input



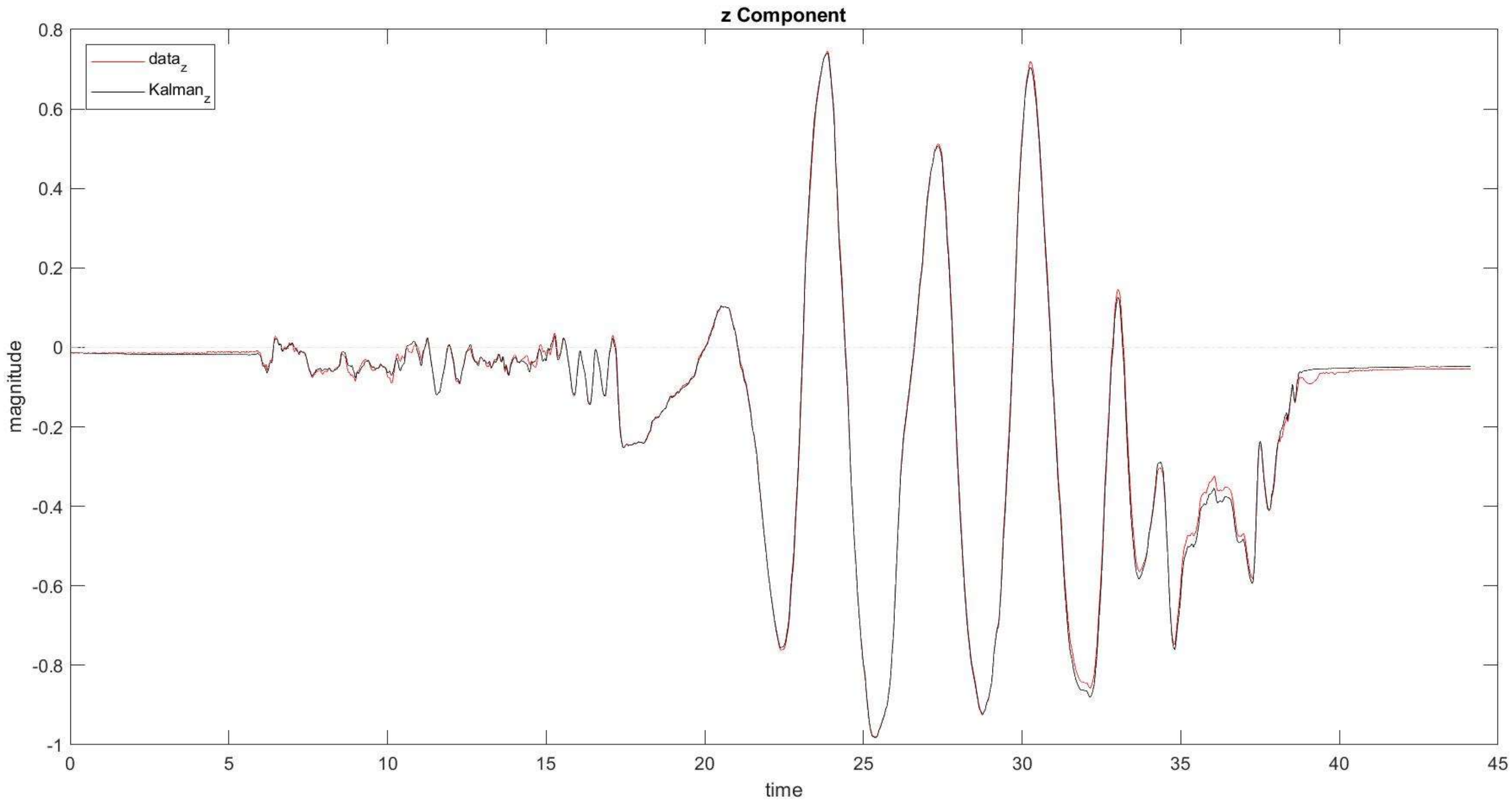
Kalman’s filter: gyro as input



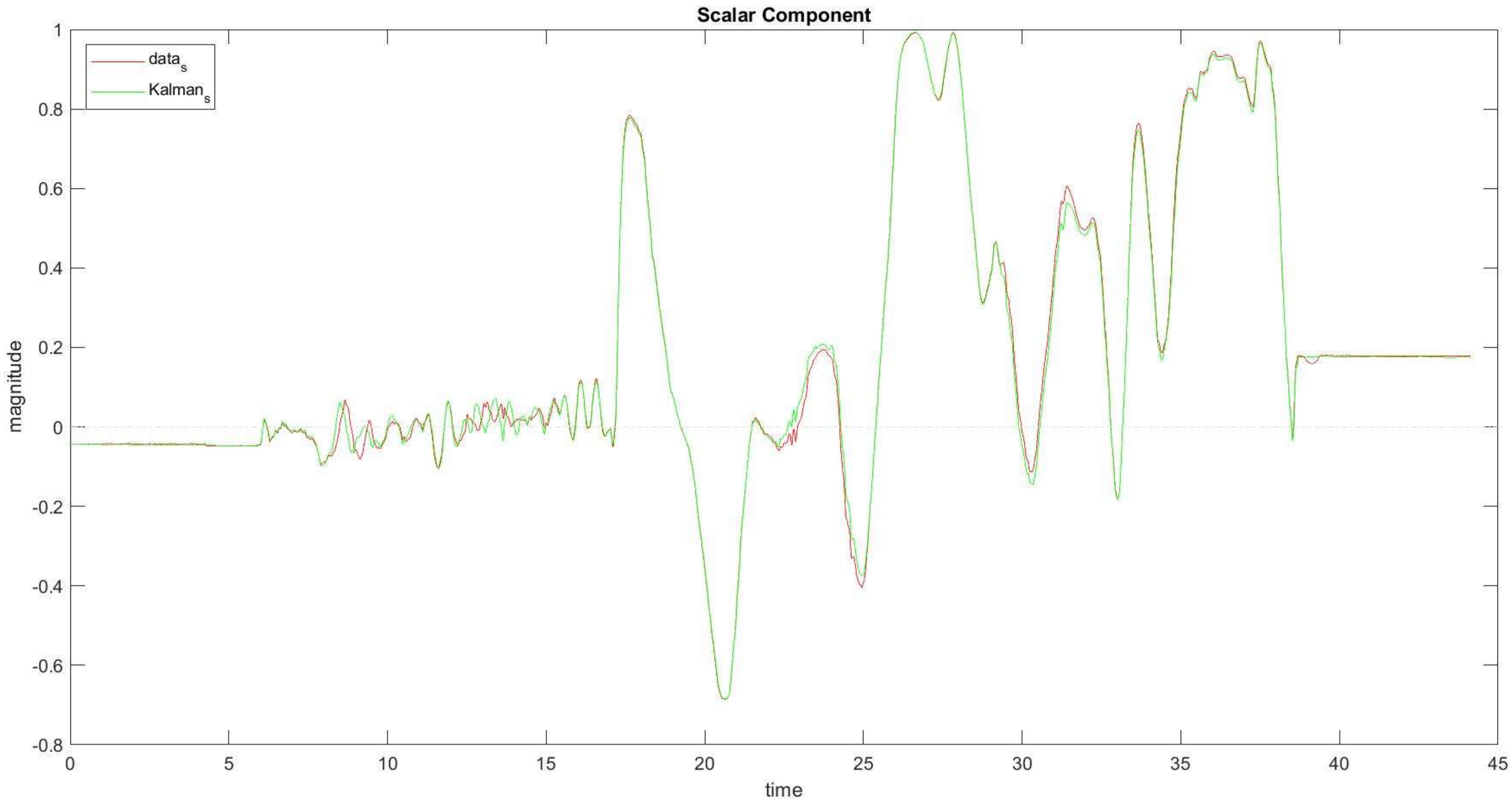
Kalman’s filter: gyro as input



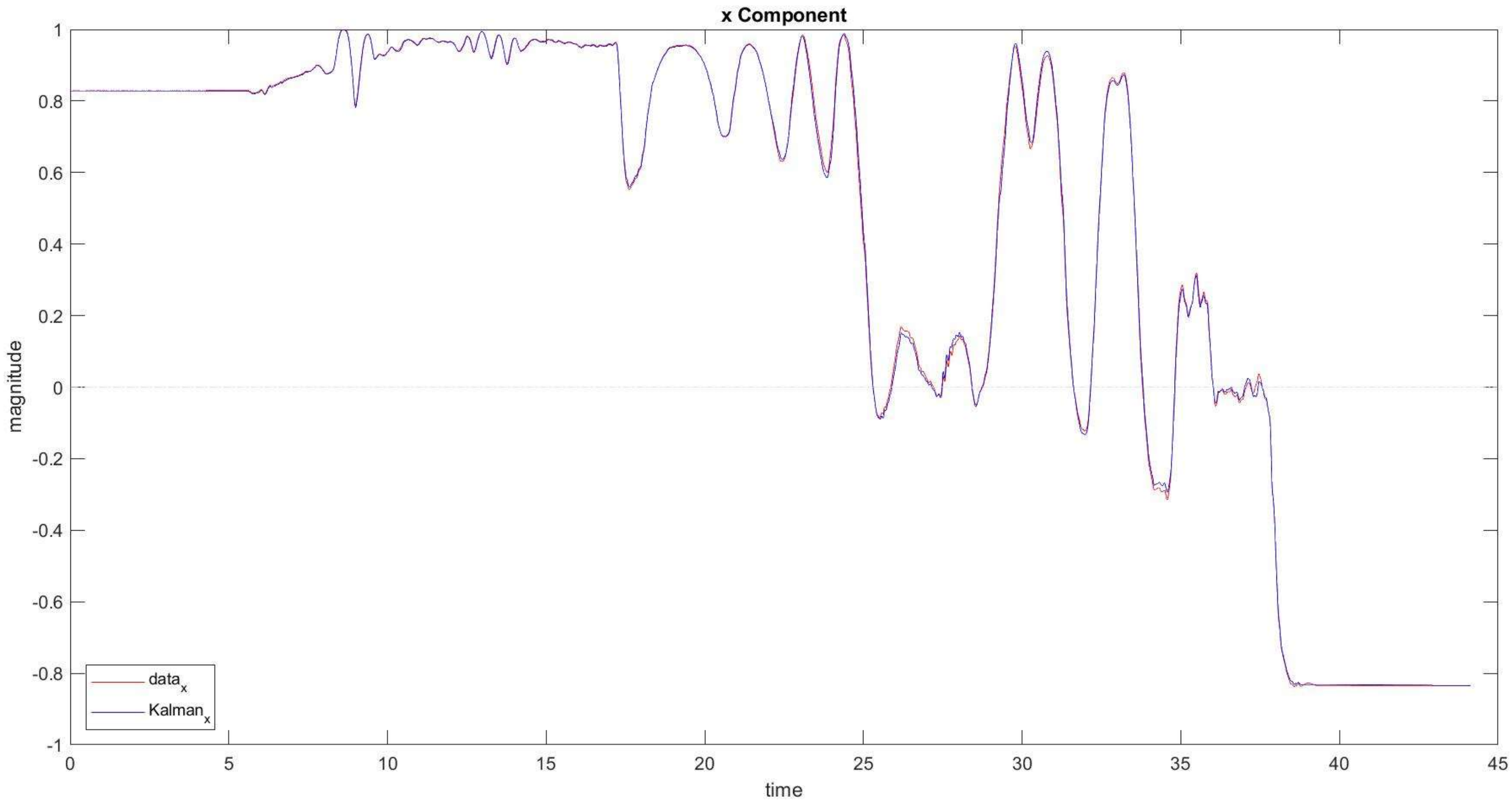
Kalman's filter: gyro as input



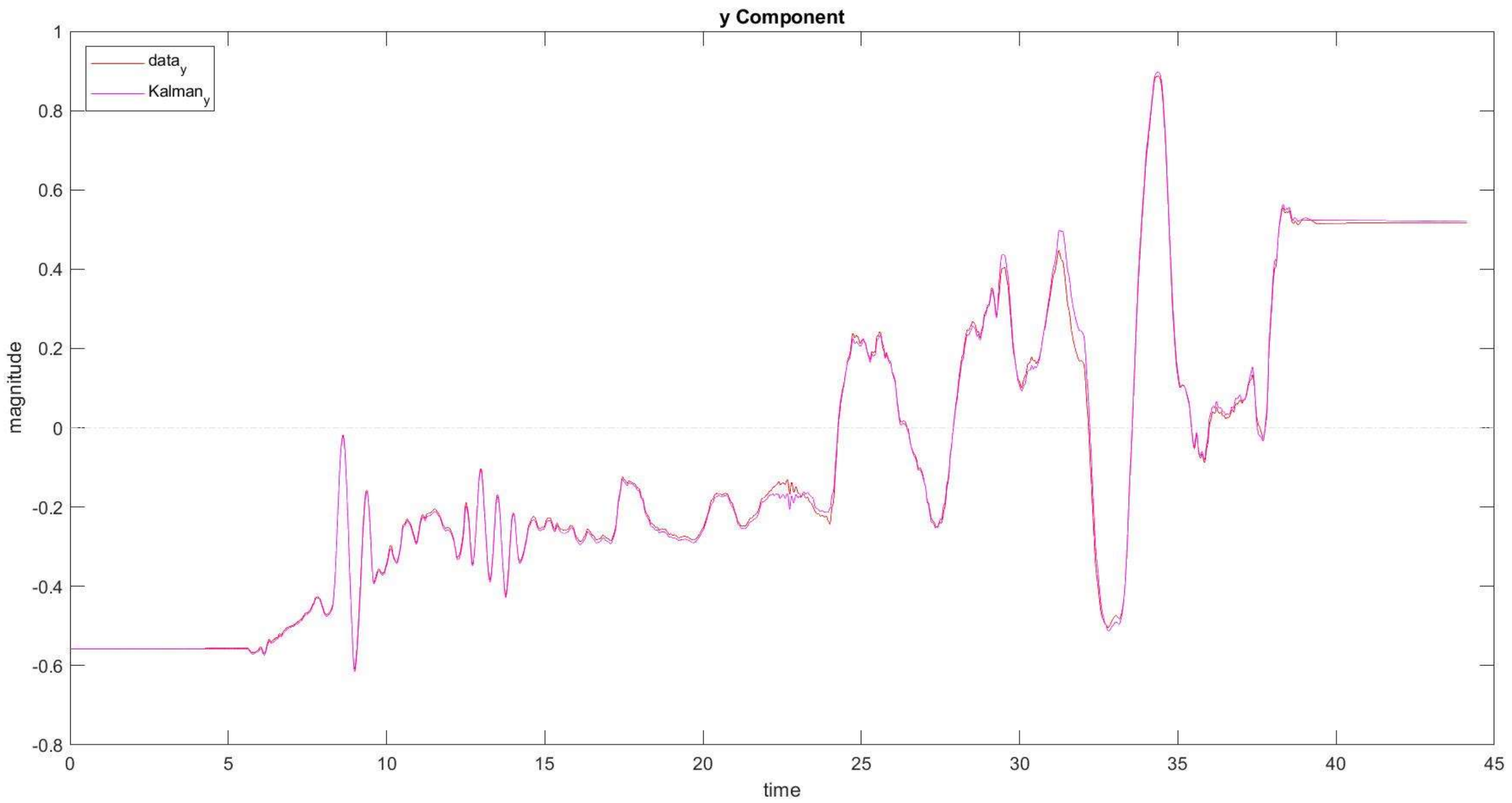
Kalman’s filter: gyro as sensor



Kalman's filter: gyro as sensor



Kalman's filter: gyro as sensor



Kalman's filter: gyro as sensor