CIS II
Seminar Presentation

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3/4/21

Motorized Fixation to Tubular Retractor in Brain Surgery

The objective of this project is to:

- Develop software to realign a retractor based on a control pad
- Develop a method of estimating the orientation of a tool (forceps)
- Integrate the method of orientation estimation into the software to realign a retractor to allow for tubular realignment based on an estimated orientation

Paper Selected: Orientation Estimation

- **Algorithm for Estimating the Orientation of an Object in 3D Space, Through the Optimal Fusion of Gyroscope and Accelerometer Information.**
  - Contreras-Rodríguez L.A., Muñoz-Guerrero R., Barraza-Madrigal J.A, 2017 14th International Conference on Electrical Engineering, Computing Science and Automatic Control (CCE), Mexico City, Mexico. September 20-22, 2017
  - **Why**: Potential Method of Estimating Orientation with IMU; useful for our realignment procedure

Algorithm for Estimating the Orientation of an Object in 3D Space, Through the Optimal Fusion of Gyroscope and Accelerometer Information.

Summary:

- Developed three different methods of estimating object orientation in space by utilizing the different types of data measured by an IMU
- Analyzed the behavior and orientation estimated for all 3 algorithms in static and dynamic situation

Results:

- Gyroscopes alone are bad estimators of orientation due to drift
- Accelerometer data can be used to compensate offset and gyro drift

Significance

The paper showed that IMUs are capable of accurate 3D orientation estimation by combining the different data that they collect, something that gyroscopes alone are not great for.

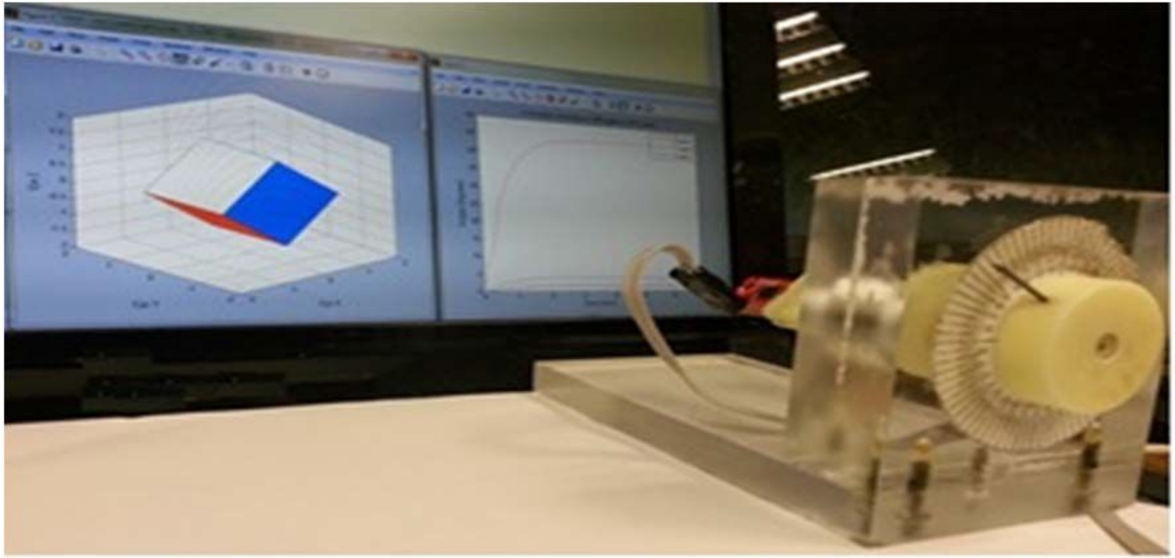
Experimental results demonstrate high accuracy in static X and Y axis orientation estimation, and dynamic X, Y and Z orientation with one of their proposed algorithms

Demonstrated that IMUs are sufficient alone for orientation estimation

May provide basis for our algorithm

Experiments

For this research, 3 algorithms were used to estimate orientation in a series of experiments in which the actual orientation of the IMU was controlled by a device.



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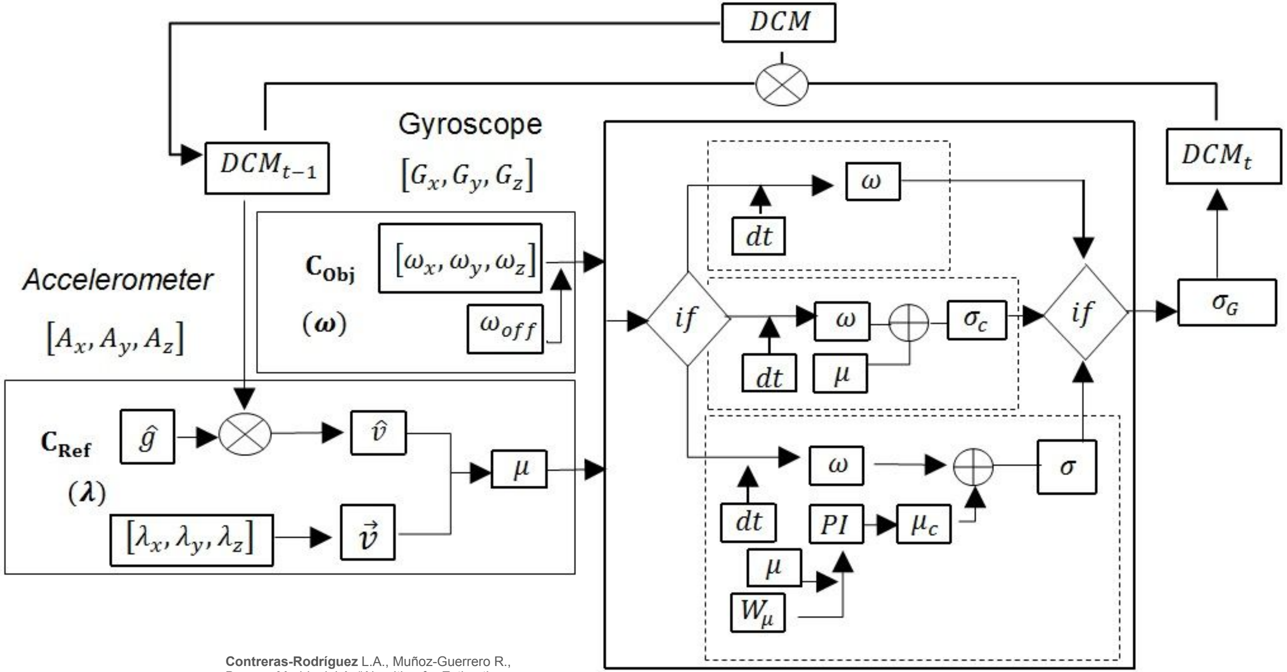
Differences between the 3 Algorithms

1. Estimates orientation σ_G by including the offset correction ω_{off} in ω (the mathematics for the offset correction will be explained later)

2. Estimates the orientation as σ_C by including both ω_{off} and μ - a correction vector for drift calculated from the accelerometer output

3. Estimated the orientation as σ using a PI feedback controller in order to update the gyroscope's estimated orientation to remove drift and reduce noise

Block Diagram of the 3 Methods



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ω - Gyroscope data alone with offset correction
σ_C- Plain estimation including gyroscope data and accelerometer data
σ - Estimating using a PI feedback controller to remove drift and reduce noise (includes gyro + accelerometer data)

Algorithm for Orientation Estimation - All Methods

Used a direction cosine matrix (DCM) to convert coordinates between accelerometer and gyroscope coordinate systems.

To speed up computation they make some assumptions and use an approximation

$$\begin{bmatrix} C(\theta)C(\phi) & -S(\theta)C(\alpha)+C(\theta)S(\phi)S(\alpha) & S(\theta)S(\alpha)+C(\theta)S(\phi)C(\alpha) \\ S(\theta)C(\phi) & C(\theta)C(\alpha)+S(\theta)S(\phi)S(\alpha) & -C(\theta)S(\alpha)+S(\theta)S(\phi)C(\alpha) \\ -S(\phi) & C(\phi)S(\alpha) & C(\phi)C(\alpha) \end{bmatrix}$$

$$\begin{matrix} \cos(\sigma) \approx 1 \\ \sin(\sigma) * \sin(\sigma) \approx 0 \end{matrix} \quad \textit{Assuming} \begin{cases} \sin(\alpha) \\ \sin(\phi) \\ \sin(\theta) \end{cases} \approx \begin{bmatrix} \alpha \\ \phi \\ \theta \end{bmatrix}$$

$$DCM = \begin{bmatrix} 1 & -S(\theta) & S(\phi) \\ S(\theta) & 1 & -S(\alpha) \\ -S(\phi) & S(\alpha) & 1 \end{bmatrix} = \begin{bmatrix} 1 & -\theta & \phi \\ \theta & 1 & -\alpha \\ -\phi & \alpha & 1 \end{bmatrix}$$

$$DCM = \begin{bmatrix} 1 & -\theta & \phi \\ \theta & 1 & -\alpha \\ -\phi & \alpha & 1 \end{bmatrix} = \begin{bmatrix} r_{xx} & r_{xy} & r_{xz} \\ r_{yx} & r_{yy} & r_{yz} \\ r_{zx} & r_{zy} & r_{zz} \end{bmatrix} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$$[\epsilon_x, \epsilon_y, \epsilon_y] = [r_{xx}, r_{xy}, r_{xz}] \begin{bmatrix} r_{yx} \\ r_{yy} \\ r_{yz} \end{bmatrix} = X * Y^T$$

$$[X', Y', Z'] = \left[X - \frac{[\epsilon_x, \epsilon_y, \epsilon_z]}{2} Y, Y - \frac{[\epsilon_x, \epsilon_y, \epsilon_z]}{2} X, (X') \times (Y')\right]$$

$$DCM = \begin{bmatrix} X_{norm} \\ Y_{norm} \\ Z_{norm} \end{bmatrix} = \left[\frac{X'}{|X'|}, \frac{Y'}{|Y'|}, \frac{Z'}{|Z'|}\right]^T = \begin{bmatrix} 1 & -\theta & \phi \\ \theta & 1 & -\alpha \\ -\phi & \alpha & 1 \end{bmatrix}$$

(Contreras-Rodriguez 2017)

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Orientation from Gyroscope Alone - All Methods

Estimating orientation with only the gyroscope data is straightforward.

The gyroscope records angular velocity in gyro coordinates and then taking the time step we can estimate the orientation (1)

However, this is prone to accumulating error as with each time step we sample, the error builds from the previous (2)

$$\sigma_G = \omega * \Delta t \quad (1)$$

$$DCM = DCM_{t-1} * DCM_t \quad (2)$$

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Offset Compensation - All Methods

Offset is the difference between the reference position and the zero position.

(i.e. there is a non-zero initial state)

$$\omega_{off} = \frac{\sum_{i=0}^{n} \omega}{n}$$

$$\omega = \omega - \omega_{off}$$

Corrected before orientation was estimated (part of data processing)

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Drifting Compensation - 2nd and 3rd Method

Drift is caused by “integration of gyroscope measurement errors” and this leads to an accumulating gyro drift.

$$\vec{v} = \frac{\lambda}{|\lambda|}$$

$$\hat{v} = \hat{g} * DCM_{G_t}$$

$$\vec{\mu} = \vec{v} \times \hat{v}$$

Rotational correction vector (μ) was estimated by by computing cross product of inertial direction vector (as estimate of local coordinate system) and gravity vector.

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Data Integration

Conventional Method (2nd)

- Feed μ back to σ_G to get a corrected orientation vector

$$\sigma_c = \sigma_G + \vec{\mu}$$

- Negatives: Potentially susceptible to high levels of noise due to acceleration

New Method (3rd)

- Implemented a Proportional Integral Feedback Controller (PI)

$$\mu_c = K_p f(W_\mu * \mu) + K_i \int_0^t f(W_\mu * \mu)\, dt$$

$$\sigma = \sigma_G + \mu_c$$

- ^ Optimal weights calculated using the “good gain method”

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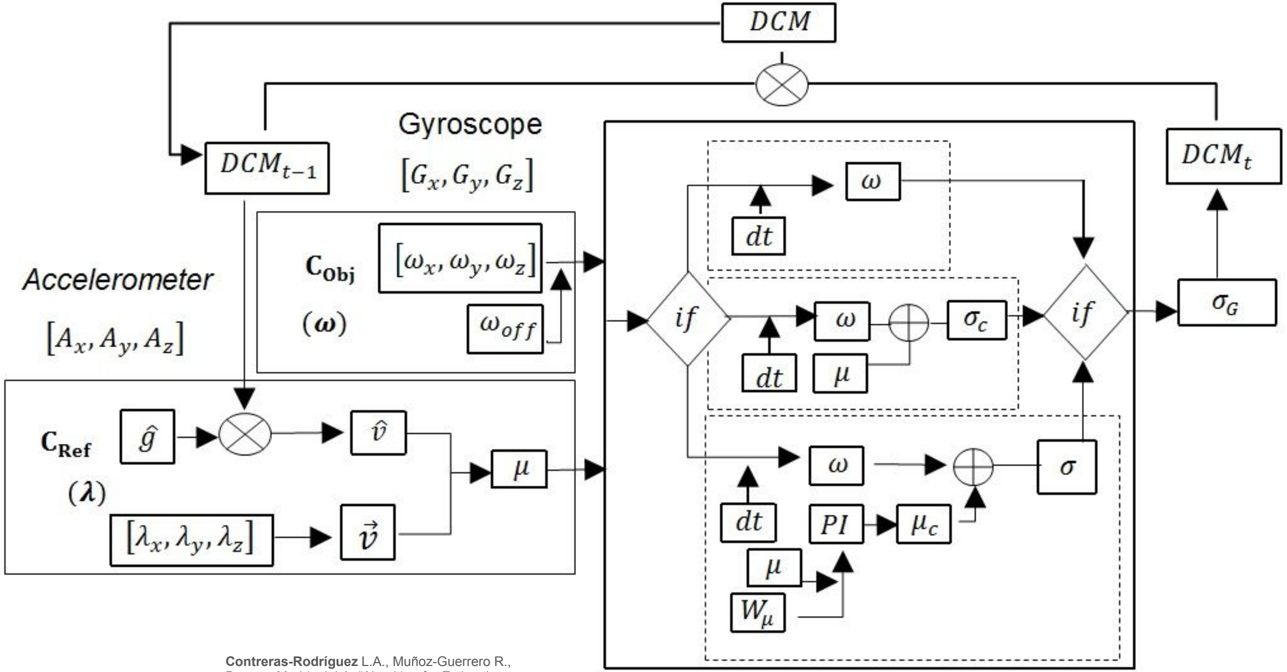
Refresher: Block Diagram of the 3 Methods



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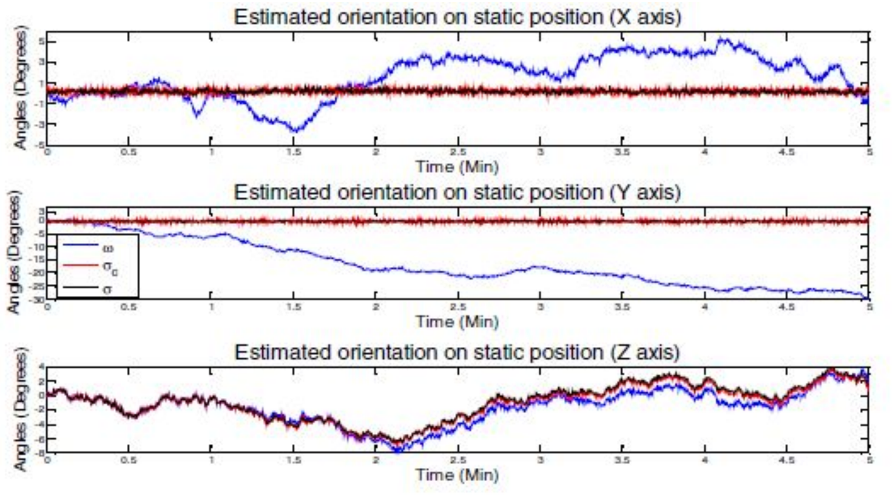
Static Experiment

For the static experiment, the IMU was kept in a static position for 5 minutes to allow for drift to take full effect.

The 3 different algorithms were applied over the whole period to determine which compensated for drift the best.



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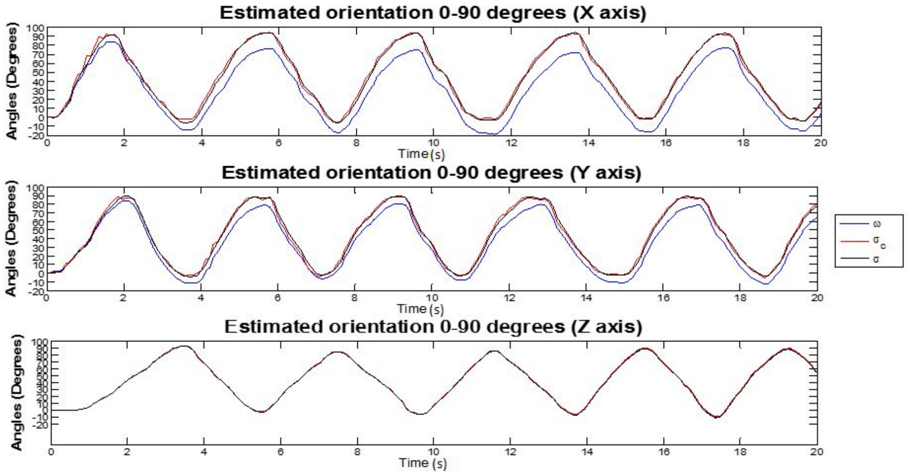
Dynamic Experiment

For the dynamic trial, the IMU was rotated periodically for 20 seconds and the 3 different algorithms were applied to demonstrate the algorithms’ respective abilities to estimate changing orientation.



Here the differences are more noticeable in the x and y axes, with the σ_C method having no significant difference from the σ method.

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Thoughts

Next Steps:

- Redoing the Dynamic Experiment for longer periods of time to allow for drift
- See how well the system works on small scale movements (0-5 degrees)
  - Perform experiments to determine the uncertainty in movements
    - How sharp of a resolution we can reach?
- **Integrate the data of several IMUs to more precisely estimate orientation of an object**
- Redoing the Dynamic experiment with sharper movements
  - Acceleration was a large source of noise, but how does the PI system handle large accelerations and decelerations.

Thoughts

Critiques:

- For the dynamic experiment, they mention they have a tool that moves the device through certain angles, but when they create the results chart, they only plot the different methods and never the actual values
- Never directly quantify the orientation they are off (i.e. no degree standard deviation, mean difference, provided)
- They cite acceleration as one of the main situations in which the new method is better than conventional data integration, but their experiments hardly take into account acceleration
- Each experiment appears to have been conducted only once - Cheap and quick experiment, why not more trials

Conclusions

- The procedure offered by Contreras-Rodriguez et al. offers a promising basis for a method of orientation estimation for our application with tubular retractors
- By combining the data received by several IMUs, we should be able to achieve higher resolution than that which was achieved by a single IMU in the paper
- The Z-axis may prove harder than we anticipated as the effects of gravity on an IMU seem to be rather large and harder to filter than we thought.

Reference:

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Thank You