Pose Estimation for Solar Boat using IMUs

Kris Van de Voorde, Rafael Berkvens
Faculty of Applied Engineering
Electronics-ICT
University of Antwerp
Antwerp, Belgium
kris.vandevoorde@student.uantwerpen.be,
rafael.Berkvens@uantwerpen.be

Simon Verspeek
Faculty of Applied Engineering
Electromechanics
University of Antwerp
Antwerp, Belgium
simon.verspeek@uantwerpen.be

***Abstract*—For this paper, the solar boat's pose will be estimated with the interest to give an impression of the boat's pose, which can be used to improve the stability. We will research estimating the pose of an object by using three different Inertial Measurement Units. The accuracy and sample rate of the data that would be achieved will be crucial factors, considering that the data will be directed to a mechanism, which will stabilize the boat again. The following results will be achieved...**

I. Introduction

The solar boat is a project by UAntwerp students that has already been in development for over 11 years. The team wants to implement a new feature to gain more stability while floating. In addition, the team added a hydrofoil to the boat, which also adds self-balancing if well calibrated. The three hydrofoils, which are attached at the bottom of the solar boat, lift the boat's hull out of the water, which reduces the contact with water. As a result of this there is less friction, which allows the boat to float faster, although this will reduce the stability if not well calibrated. This paper aims to provide an analysis of how electronics can be used to give an accurate and real-time estimation of the pose. The research will be implemented in the existing structure of the solar boat. To stabilize the boat there is a minimal need of 3Dof. A mechanism that would be implemented next year can use this data to stabilize the boat. When there is the need for a pose/orientation estimation there is a requirement for a 6Dof, which contains information about the rotation around the x-axis (longitude axis) and the x-axis itself. The rotation around this axis may be referred as the roll. It also contains the rotation around the y-axis (lateral axis), or pitch. Finally it contains the rotation around the z-axis (vertical axis) or yaw. Respectively the acceleration on the different axes can be designated as surge, sway and heave. The axes can be seen in fig: 1 [1].

Hendrik J. et al. [2] introduces a way to estimate orientation with gyroscopes and accelerometers. The sensors used in this paper are three miniature gyroscopes (Murata ENC05E) and three linear accelerometers (AD x105). First the angular momentum received by the gyroscope is integrated, afterwards the Z-rotation and tilt are split. The tilt received from the accelerometer will then be subtracted from the tilt obtained after splitting. The result of the subtraction then will be put as

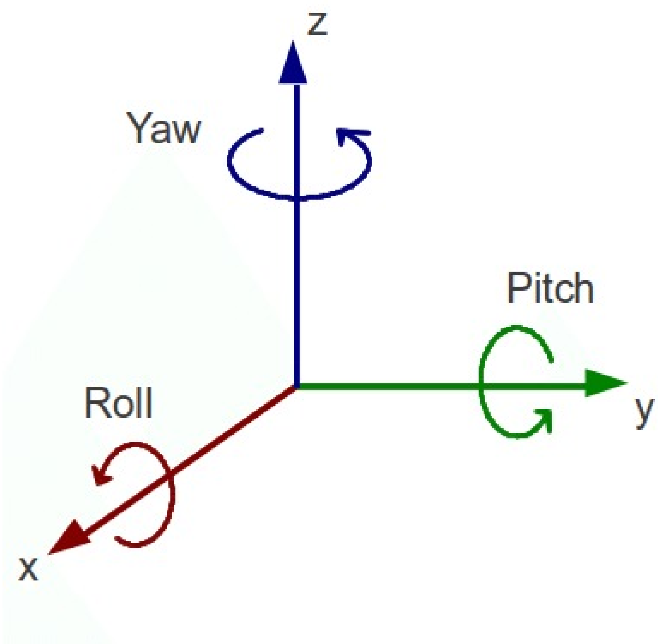

Fig. 1. Pitch, roll and yaw

input in a Kalman filter. The result of the Kalman filter will then be subtracted from the tilt received from the splitting. At last the Z rotation and the last result will be fused. The result of the experiments show that the combination of the gyroscopes with accelerometer can give better results. Another problem is that the rotation around the Z-axis can be inaccurate (drift). However, the tilt measured from accelerometers is less accurate when the object is moving. Some alternatives in the paper are given to get more accuracy for the latter. This research is based on previous work of J. E. Bortz [3].

Young [4] used different kinds of sensors together. The setup consists of a 3D gyroscope, a 3D accelerometer, and a magnetometer. The author also uses an adaptive method, which means that when there is external acceleration there will be added smaller weight to the accelerometer output. The author also uses an indirect Kalman filter, which receives the data as quaternions. An indirect Kalman Filter is a Kalman filter of which the purpose is to estimate the orientation error instead of directly estimating the orientation, which gives an advantage that the state dimension is smaller, which gives a faster response. As a result of this paper, we can expect that when using an adaptive filter the data will be more accurate when there is also external acceleration. This method does not compensate the magnetic disturbance, which can be seen in the results.

A. Kim et. al. [5] uses the combination of 3D accelerometer with a 3D gyroscope to present a real-time orientation estimation algorithm. This paper also uses a Kalman filter and quaternions. In this setup, it is possible to correct the yaw angle error drift. Accelerometers are used as a corrective measurement. To compare the result of experimentations this paper makes use of an optotrak camera to track the position of different LEDs. Even the yaw angle is calculated well. However, We can still use a magnetic sensor to improve the position of the yaw angle.

J. L. Marins et. al. [6] introduces a rigid body real-time estimation orientation, which makes use of a MARG (Magnetic, Angular Rate, and Gravity) sensor. A MARG combines three-axis accelerometer, a three-axis magnetometer, and a three-axis gyroscope. This method makes use of an algorithm called the Gauss-Newton iteration algorithm to find the best quaternion that relates to the earth's magnetic fields, which is measured by the magnetometer and measured accelerations. That quaternion will be the input of a Kalman filter, which makes it possible to do a real-time orientation estimation. The research first makes use of an Extended Kalman filter, which has a seven states and nine outputs. These nine outputs are directly measured from the MARG sensor. Resulting in a highly non-linear equation, due to the non-linearity the Extended Kalman filter becomes a complicated one, which delays the result, making it less viable for real-time applications. The second approach uses the Gauss-newton algorithm, which is more applicable for a real-time application. The converge occurred after some tracking. This approach would apply to highly maneuverable objects like the solar boat. This paper builds upon [8] that makes use of a complementary filter.

Pose Estimation is a concept that is also often used in many other sectors. This concept is also commonly used in areas such as rehabilitation. However, for this paper, it is more interesting for vehicles, which in this case will be a solar boat. There are many possible kinds of technology possible to realize pose estimation. In this paper three IMUs (Inertial Measurement Units) will be used to receive a pose estimation.

The data obtained by the IMU has to be received and calculated in real-time. Considering that the system based on the data will have to self-stabilize. Likewise the orientation accuracy also plays an important role. In this paper the different algorithms will be described, considering the sample rates.

Also, there are some alternatives to measure pose estimation. An example is the use of different cameras. However, in this case, it is impossible to use due to an unmanageable environment. Still, this technology will be used to calculate the ground thruth, which will be used to compare the accuracy delivered by the IMUs implemented in our set-up.

In this paper, there will be an overview to see what kind of methods already exists and what their advantages and disadvantages are. Furthermore, the different materials and methods that will be implemented to estimate the roll, pitch and yaw of the boat will be described. Finally, the accuracy results of the tests will be described.

II. Existing structure solar boat

The main objective is to increase stability by making use of three different IMUs. The solar boat already contains a 3D-axis accelerometer, which is included into a module referred to as the ESX TC3GGPS. The ESX TC3GGPS is mainly used as a GPS(Global Positioning System), which pushes the received coordinates as a CAN (Controller Area Network) message through the data bus. This can be seen in [7]. This accelerometer will not be used for estimating the pose of the solar boat. However, the module will be used to send the computed data to a server for analysis. Another participant of the solar boat is testing the use of a 2D gyroscope, which could be used to compare data received by the different IMUs.

The thesis explicitly involves the use of IMUs. Briefly, it will indicates about the acceleration and rotation of a rigid object. By using this data, the boat can be kept straight by the pilot or a system that can implement a self-balancing physical setup, which handles the data from the IMUs. This technology can be used in other applications as well.

A. Accelerometer

Accelerometers use a mass attached to a spring on both sides, which depends on the applied external force. It causes the mass to move in a direction, which will shorten one of the springs attached to it. The springs attached to the mass will pull it back to the center. How a sensor will measure the position of the mass depends on what kind of accelerometer is used. One of the sensors that has excellent characteristics are MEMS (Micro-Electro-Mechanical Systems) accelerometers [8] [9], which will be used for our project. The Accelerometer senses the force that applies at a specific moment, which means that the output will be the acceleration in one of the axes depending on how the accelerometer is oriented. When using a 3D-axis accelerometer, it is possible to measure the acceleration on the different axes. The use of acceleration has a significant advantage; the accelerometer does not need to make a calculation on the previously generated values. Hence the integration drift can be left out of account, which means that the data will not get off track although it has no way to calculate its position while starting. The accelerometer will calculate a relative position. Another known problem of the accelerometer is its bias. The bias will cause inaccurate data, which lets the estimated data points fluctuate neighboring the exact point. However, those problems can be resolved by calibrating the accelerometer at the start or to combine different kinds of sensors.

When there is no external acceleration, the accelerometer gives a better output than an accelerometer enduring external acceleration, which is detectable When the gravity norm is not near $9.8m/s^2$. This is the reason why the author of [4] will use a combination of gyroscopes when external acceleration is expected. This could be handled by giving the accelerometer less weight in the equation, which has been explained in [4].

It's impossible to calculate the yaw with the use of the accelerometer, due to no force is detected when you rotate around the z-axis. Still with the use of a gyroscope and a magnetometer it is possible to calculate the yaw degree of an object. We will use the accelerometer mainly for the roll and pitch witch can be fusioned with the gyroscope.

The roll and pitch with the us of the accelerometer can be calculated with the following equation:

$$\Theta = \frac{\tan \frac{A_y}{A_z}}{\pi} * 180$$

$$\Phi = \frac{\tan^{-1} A_x}{\sqrt{a_y^2 + a_z^2 \pi}} * 180$$

The accelerometer i

B. Gyroscope

The MEMS gyroscope does not use rotating parts, which is an exception compared to the typical gyroscopes. The MEMS gyroscope makes use of a mechanically vibrating element to sense the angular momentum of a rigid object.

in article [10], the author describes different key elements how to compare the quality of different MEMS gyroscopes. It also gives an overview of the different bias, which can manipulate the outcome of the gyroscope data.

Also, the gyroscope depends on the previous results, which means that there is a possibility for drift as a result of integrating the results [8] [9]. One will have the advantage to know the absolute position with the gyroscope, still, after some time the data received by the gyroscope will be inaccurate. This problem is known as drift [8].

With the gyroscope it is possible to calculate pitch, yaw and roll. to caclulate those three variables with a gyroscope is pretty simple, we just need to integrate.

$$\Psi = \omega_\Psi * dt$$

$$\Phi = \omega_\Phi * dt$$

$$\Theta = \omega_\Theta * dt$$

C. Magnetometer

A magnetometer can be used to detect gravitational changes happening relative to the rigid body. Magnetometers can be classified in two different categories; Hall effect and magneto-restive effect. In our set up we will make use of the Hall effect.

The magnetometer is a great tool to improve the accuracy in motion tracking. In our case we will also use a MEMS 3D magnetometer. Paper [11] describes the working flow of a magnetometer used in an IMU (MPU-9150) [8] [9].

TABLE I
IMU DEFINITION

	Acelerometer	**Gyroscope**	**Magnetometer**
Characteristic	Acceleration	Angular momentum	Magnetic field
Units	$\frac{m}{s^2}$	$\frac{m}{s}$, $\frac{rad}{s}$	T
Definition	X,Y,Z	roll, pitch, yaw	X,Y,Z

We will mainly use the magnetometer to calculate the heading of an object. With the following formule one can calculate its yaw:

$$\Psi = \frac{\tan -1(\frac{M_x}{M_y})}{\pi} * 180$$

Still this formula is incorrect in case of tilting an object. To calculate the true heading we will also use accelerometer data.

$$M_x = m_x \cdot \cos(\phi) + m_z \cdot \sin(\phi)$$

$$M_y = m_x \cdot \sin(\phi) \cdot \sin(\Theta) + m_y \cdot \cos(\theta) - m_z \cdot \cos(\phi) \cdot \sin(\Theta)$$

$$\Psi = \frac{\tan -1(\frac{M_x}{M_y})}{\pi} * 180$$

D. combining accelerometer, gyroscope, magnetometer

Combining an accelerometer, gyroscope and a magnetometer can improve the pose estimation to give more accurate data or to gather more degrees of freedom. Combining those sensors can be referred as IMU (Inertial Measurement Unit). In [12] the author describes a way to combine a 3D accelerometer with a 3D gyroscope. The author also describes how a Kalman filter works.

If we place the IMUs on three different positions, then the angular momentum and magnetic field should stay the same if there is no noise on the sensors. We can still use the data of those sensors to filter some noise out. Only the acceleration on the different position will change. When doing a pitch the accelerometer at the west and the east of the set up will have more acceleration, which could lead to more precious pitch estimation.

E. Modelling

Afterwards, the raw data received from the different sensors cannot be merely accepted. The various data points need to be represented in a way that allows light weighted manipulation, while still being accurate. A model that can be used is the rotation matrix, which uses a 3X3 matrix. The rotation matrix has the advantage to be free from gimbal lock [8], which is caused when two or more axis are driven into a parallel configuration, due to gimbal lock there will be a lost of one degree of freedom. However, the computation time is higher, which will make it harder to have a real-time system. Euler angles are also frequently used for modeling, this way it may compute faster. However, the disadvantage will be the problem of gimbal lock, which means it will have a data loss of one degree of freedom. A good alternative can be found

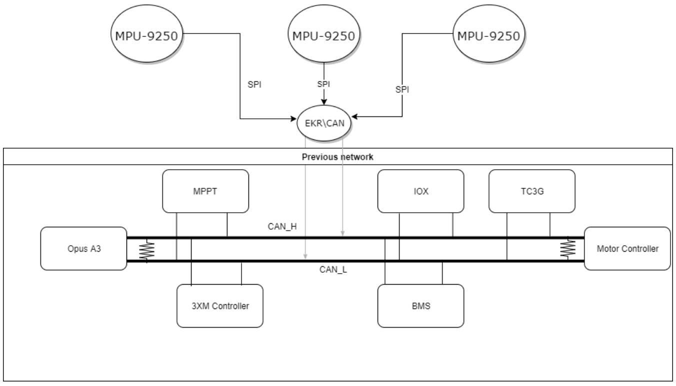

Fig. 2. Connection components

in quaternions, which are described in [12]. Quaternions are a lightweight way to compute orientations. Likewise, it is also free from gimbal lock. The use of quaternions [8] is more complex than the former models.

F. Filters

Once the date is gathered from the accelerometer or additional sensors we can use different kinds of filters. To remove noise, there are various possibilities. One may use a digital filter (i.e a low pass filter) for reduction of fluctuation of the acceleration data. However, if needed, there is also a possibility to use filters for fusing different kinds of measurement data. The filters used in [8] [9] [12] are primarily complementary filters and Kalman filters. The complementary filter just adds data of different sensors with a percentage, which makes the complexity of the filter easy to understand. The Kalman filter, which makes use of probabilities, is a lot harder to understand. The Kalman filter can estimate in what pose the boat will be, based on data from different kinds of sensors. It is possible to know what the state of the boat currently is. In addition it also adds a nice feature to estimate the future state of the boat. This filter also allows eliminating noise. A Kalman filter can also work with just the use of Accelerometer data.

G. Set up

The first set up for testing will be as followed, one IMU centered at the solar boat will be used to estimate the pose. A microcontroller named Arduino DUE will be used to process the data. The connection between the Arduino DUE and the IMU can be handled with two different protocols. In our case we are going to use SPI. because of SPI we can have a better rate of data that is sending between the sensors. https://aticleworld.com/difference-between-i2c-and-spi/. Still in the solar boat we prefer to use a communication protocol as CAN or UART because of the distances, which are a lot further than our set up.

The set up in the boat for the different IMUs will be as followed, we will add three different IMUs, which are MPU-9250, being spread across the boat see fig: 3, 2 they will be connected over a protocol called SPI. In this case we prefer SPI, which has a better length reach. We will also make use of an Arduino DUE to process the data and apply it to a filter. We prefer Arduino DUE because of it processing power but also the pins that are working on the same voltage levels as our sensors. With those three different IMUs it is possible to calculate the VIMU (Virtual Inertial Measurement Unit), which will be oriented towards the center of the boat. Each of the three different IMUs will be oriented each in a different way. Using multiple IMUs, a Kalman filter will be required, which can be used in combination with a Gauss-Newton algorithm due to the non-linearity state equation. The Kalman filter can also be used to receive real-time results. The non-linearity is caused by the rotation and translation due to the different positions and rotation of the IMUs.

In both cases, the modeling will be done with quaternions. The Arduino DUE has more processing power than an Arduino uno. It will also make the set up less complex than a standard Arduino uno. Furthermore, the pins are at the same voltage level as the sensors which are being used in our set up. Another advantage thanks to Arduino DUE, it contains two pins; CANtx and CANrx, which could be used to reduce the complexity of the circuit for the connection with the CAN bus.

To measure the accuracy of the output data, the data will be compared to the ground-truth, which is the proper objective (provable) data for the different tests of a rigid object. It is not possible to measure the ground truth of the whole boat, however, we can make a small scaled version of the solar boat. This way the scaled boat can be moved easily and with the use of cameras, one can calculate the exact orientation of the boat. The different algorithms can be tested on accuracy. Afterwards, the frequency of the received data can be compared.

H. Method

At first we will calibrate the three different accelerometers and gyroscopes to get more accurate readings. This calibration will be done on the Arduino DUE itself. file:///C:/Users/Kris/Documents/BMS/sensors-14-14885.pdf describes a way to callibrate the 3D gyroscope and 3D accelerometer.

for both sensors we will use the next equation

For this you break down the data into regions that are close to linear and form different A and B matrices for each region. This allows you can check the data and use the appropriate A and B matrices in the filter to accurately predict what the state transition will be.

$$q = C_S(q_S - q_0)$$

where q_0 is the column vector, which describes the zero-level offset of the sensor. C_S describes the callibaration matrix it depends on the sensitivity of the axisses. q_S are the three axisss value we receive from the sensor. C_S and C_0 are the variables we need to calculate to use it for correction the raw data received by the sensor q_S

To calibrate the accelerometer, the accelerometer will need te get some samples on six different position. The first three position are ...

In the caseof the Accelerometer

$$C_S = 2(A_{S\_} - A_{S+})$$

where $A_{S\_}$ are the value detected on the negative position and A_S+ are the values detected on the psitive position. Different samples will be taken, how more samples are taken the better we could reduce the noise. The average of the samples are used, so we We can find Q_0 by the following formule

$$Q_0 = \frac{(A_{S-} + A_{s+}) \cdot i}{6}$$

Whereas I will be a vector of ones.

$$i = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

To callibrate the gyroscope the first measurement is at rest, this way we can find the zero level offset.

$$q_0 = q_s$$

In our code we will calculating the sensitivity on the basis of scal we are choosing. Still the level zero bias will be alculated with getting al ot of samples

As next we will use differnt filters on one IMU.

- Kalman filter
- complementary filter
- Magdwick filter

The filter will be implemented in Matlab

ing the +- 500 degrees/s max range for angular velocity(not that fast), but the benefit is the smaller the max range the more accurate the gyroscope reading will be

As can be read in the indrocuction section the normally for non-linear inputs is to use an extende Kalman filter. If we want to introduce the extended kalman filter we're getting a filter that is not compatible to get real-time values. So a nice alternative to this filter is to use an kalman filter where we are making some accelerometer data linaer.

Afterwards we will combine the the output of the three different imu's to calculate a common orientation estimation.

Hier komt de beschrijving van de extende kalman algoritme die gebruikt gaat worden. (formules etc...) + een kleine beschrijving of verwijzing naar de paper van de camera accurancy test implementatie

III. Results

In this section we will show the different data regarded to the accuracy that are received from different tests. We will also look at the frequency of received data, which will be written down in a table, based on samples/seconds. The tests will be compared with graphs, which are based on the different readings. For each test there should be a yaw, roll and pitch received from the IMU compared to the yaw, roll and pitch received from the ground truth method.

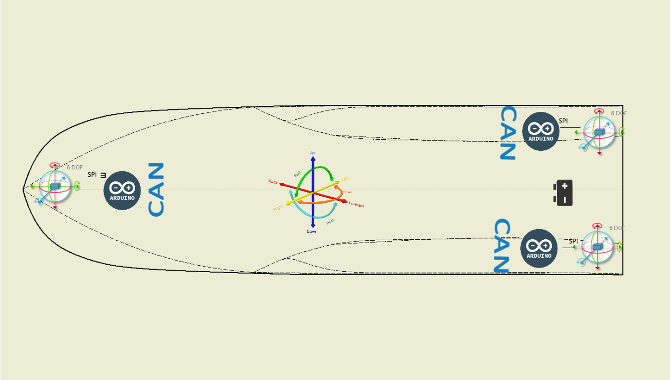

Fig. 3. Set up

We will compare the different kinds of filters that are being applied. We will also compare the difference between one IMU and the use of three different IMUs.

Then the different results will be compared to the ground truth. We will make us of a system called Qualisys. Users KrisDocuments BMS Qualisys_Quickstart.pdf. which are six different camera's that can track infrared components. With this information Qualisys can calculate a accurate 6DoF of the component.

IV. Conclusion

In this section we are going to make a statement based on the different tests.

Many methods are already deployed for orientation and pose estimation. In this section there will also be a comparison between our results and the results within the literature review, which have been described earlier in this paper. Most of those methods make use of different kinds of sensors.

V. Future work

In this section we will describe research that can improve the accuracy.

References

[1] J. Melin, "Modeling, control and state-estimation for an autonomous sailboat," Ph.D. dissertation, UPPSALA Universitet, 2015.

[2] H. Luinge, P. Veltink, and C. Baten, "Estimating orientation with gyroscopes and accelerometers," vol. 7, no. 6, pp. 455–459, 1999.

[3] J. E. Bortz, "A new mathematical formulation for strapdown inertial navigation," *IEEE Transactions on Aerospace and Electronic Systems*, vol. AES-7, no. 1, pp. 61–66, Jan 1971.

[4] Y. Soo Suh, "Orientation estimation using a quaternion-based indirect kalman filter with adaptive estimation of external acceleration," vol. 59, pp. 3296–3305, 12 2010.

[5] A. Kim and M. F. Golnaraghi, "A quaternion-based orientation estimation algorithm using an inertial measurement unit," in *PLANS 2004. Position Location and Navigation Symposium (IEEE Cat. No.04CH37556)*, April 2004, pp. 268–272.

[6] J. L. Marins, X. Yun, E. R. Bachmann, R. B. McGhee, and M. J. Zyda, "An extended kalman filter for quaternion-based orientation estimation using marg sensors," in *Proceedings 2001 IEEE/RSJ International Conference on Intelligent Robots and Systems. Expanding the Societal Role of Robotics in the the Next Millennium (Cat. No.01CH37180)*, vol. 4, 2001, pp. 2003–2011 vol.4.

[7] K. Heyvaert, M. Weyn, and W. Janssens, "Optimized sensor communication of the ua solar boat," Master's thesis, University of Antwerp, 2017.

[8] C. M., "Experimental validation of xsens inertial sensors during clinical and sport motion capture applications," Ph.D. dissertation, University of Padova, 2012.

[9] S. M., "Signal processing and pose estimation using accelerometers," Ph.D. dissertation, Universiteit Utrecht, 2015.

[10] V. Passaro, A. Cuccovillo, L. Vaiani, M. De Carlo, and C. E. Campanella, "Gyroscope technology and applications: A review in the industrial perspective," vol. 17, p. 2284, 10 2017.

[11] D. Ettelt, P. Rey, G. Jourdan, A. Walther, P. Robert, and J. Delamare, "3d magnetic field sensor concept for use in inertial measurement units (imus)," *Journal of Microelectromechanical Systems*, vol. 23, no. 2, pp. 324–333, April 2014.

[12] M. Kok, J. D. Hol, and T. B. Schn, "Using inertial sensors for position and orientation estimation," *Foundations and Trends in Signal Processing*, vol. 11, no. 1-2, pp. 1–153, 2017. [Online]. Available: http://dx.doi.org/10.1561/2000000094