Sensor motes in a multiphase medium

*Exploration of the possibilities in a two phase bubble column*

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1. Introduction

A bubble column is a multi-phase reactor consisting of a liquid and a gas phase. These kinds of columns are widely used to induce mass transfer from the gas to the liquid phase or vice versa. Bubble columns are very important for different sectors[1] using techniques such as hydro formylation, oxidation of Montan waxes[2], production of phenol via cumene oxidation[3] and fermentation of methanol to proteins. Bubble columns are important especially in the sector of biotechnology[4] i.e. for fermentations and for waste water treatment[5]. This is because favorable mixing causes mass transfer rates from the gas to the liquid phase to be sufficiently high[5].

Some important parameters are the flow regime, pattern and structure[2], since they describe the two-phase gas/liquid flows[6]. These different parameters can determine whether the flow regime is either turbulent (heterogeneous) or laminar (homogeneous)[7]. In the homogeneous flow regime the bubbles have a narrow size distribution and are spread evenly over the cross section of the column[8]. At higher gas flow rates the even distribution vanishes due to coalescence of the bubbles and a heterogeneous regime occurs. This heterogeneous regime is undesired due to large bubble sizes and high gas flow rates, because this gives low interfacial area and short transfer times.

Conventional bubble columns have a very simple design and good mixing properties but may allow back-mixing in both the gas and liquid phase, which is undesired. Also the short gas-residence time and low interfacial area due to coalescence of the gas are problems coped with in bubble columns[9]. In order to improve bubble columns, these problems need to be tackled by first characterizing the behavior of bubble columns.

Image analysis techniques are very good tools to investigate the behavior of the gas phase[9], but the liquid phase has been found difficult to characterize because it is found difficult to follow a specific particle.

Sensor motes offer a potential solution to this issue by performing in situ measurements in a 3D-system. When an equal density is approached for the motes to the medium the motes are able to flow with the medium. These spherical sensor motes (Xploring WiseMotes™, XWMs)[10] are equipped with an Internal Measurement Unit (IMU) (containing a gyroscope, accelerometer and magnetometer) that tracks acceleration, rotation and magnetic field, all triaxial. Also an internal ultrasound emitter can be equipped making it possible to also track location, which is specifically interesting for velocity measurements. The retrieved data show unique patterns that are a result of the fluid dynamics of the system. This makes the XWMs useful for characterizing fluid behavior inside of a closed or difficult to access column or tank. By measuring the mote dynamics, i.e. collisions with walls or bubbles that deliver small peaks in the accelerometer data, the mixing process can be sketched. Data in between collisions tell something about local medium phase dynamics, describing turbulent or laminar flows. Collisional data can also indicate local phase fraction.

The aim of this project is to better understand the fluid dynamics in a bubble column. The main question here is if sensor motes have capability of describing the fluid dynamics in such systems. What can, and what cannot be measured with sensor motes? What can a mote do related to bubble columns and can computational fluid dynamics (CFD) be validated by sensor motes? There is especially interest in measuring soft collisions (collisions with bubbles, not the reactor wall) and positioning with the sensor motes in order to help characterize the regime.
It is hypothesized that the XWMs will be able to distinguish between soft and hard collisions providing information about bubble size, collision frequency and average gas holdup. This will be the scope of this work.

2. Concept

2.1. Technical properties
The XWMs are designed to be able to inject a device in a fluid environment to capture and store data. In order to do so XWMs consist of an internal IMU. XWMs are capable of holding different weights to obtain an adjustable density making them suitable for measurements in different fluids. In table 2.1 an overview of the technical properties and specifications of the XWMs is given. Figure 2.1 shows what the motes look like, with on the left the IMU attached to a base and on the right the capsuled IMU.

<table>
<thead>
<tr>
<th>Functionality</th>
<th>Triaxial gyroscope</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Triaxial accelerometer</td>
</tr>
<tr>
<td></td>
<td>Triaxial magnetometer</td>
</tr>
<tr>
<td>Maximum sample rate and range</td>
<td>760 Hz; 245-2000 DPS</td>
</tr>
<tr>
<td></td>
<td>1600 Hz; 2-16 G</td>
</tr>
<tr>
<td></td>
<td>100 Hz; 2-12 GS (10^{-4} T)</td>
</tr>
<tr>
<td>Shell material</td>
<td>Poly-amide 12 (PA 12)</td>
</tr>
<tr>
<td>Battery</td>
<td>0.5 Wh rechargeable Lithium</td>
</tr>
<tr>
<td>Communication</td>
<td>Micro-USB</td>
</tr>
<tr>
<td>Measurement time</td>
<td>1 hour (at maximum sample rate)</td>
</tr>
<tr>
<td>Diameter</td>
<td>39 mm</td>
</tr>
<tr>
<td>Density</td>
<td>0.62-2.2 kg/dm³</td>
</tr>
</tbody>
</table>

2.2. Approach
In order to know what XWMs can mean in the field of multiphase flows, different motions have been characterized to understand the data. Starting with simple motions like rest, spins, pendulum motions etc., then characterizing hard/soft collisions and finally exploring multiphase media by characterizing collisions with bubbles and typical bubble column data. All the results were compared i.e. single bubbles with bubble train. Also correlations between gyroscope, acceleration and magnetic results were made to really get an understanding of the XWMs motions. To refine the data a Matlab script was made which can be found in appendix A. This script was used to process the data and create plots. Because the acceleration, gyroscope and magnetic data measure in different frequencies there are multiple results for “one time unit”. To compensate this, the mean is taken of the two measurements with the highest measurement rate for one time unit.

More experiments were done to get an understanding of the data produced by the mote but these are not included in the report itself. See appendix B for these experiments.
3. Basic experiments

3.1. Calibrations

3.1.1. Time

The axes of the XWM are as displayed in figure 3.1. As can be seen, the y-axis of the XWM is vertical, so this should measure the gravitational acceleration (1G) at rest. In order to calibrate the timescale of the XWM, which is originally in number of iterations, the mote was placed at rest for exactly four minutes as can be derived from the acceleration data from figure 3.2 (constant acceleration). When this measurement is normalized to a normal timescale the graph in figure 3.3 is the result. Now the x-axis has a timescale in seconds so that data interpretation goes easier when i.e. comparing to a video of the experiment. For the Matlab script that reads the data see appendix A.
3.1.2. Defining the experiment

In this measurement the mote was placed in rest, but several actions are taken to define the experimental part since the mote starts measuring when it is turned on. Results are displayed in figure 3.4.

What we clearly see is five stages: the point where the mote is turned on and the point where the measurement is started with three taps on the table (the three peaks in the acceleration at around 7s) as seen in figure 3.5.
Then the mote was put on the table, which brought some (in hand) spinning with it, clearly seen in gyroscope data between 7.6 and 9.5s and in figure 3.6. After that it was laying at rest on the table (between 9 and 16s). Lastly the mote is picked up again, three taps on the table and then turned off (three peaks in acceleration at 16s). What can be seen in the magnetic data is the orientation of the mote that changes. This is because the mote is picked up and changes orientation from the earth’s magnetic field.

3.1.3. Acceleration
In this experiment the mote was placed at rest. A zoomed in version of the data when the mote is completely still (6-7s) is shown in figure 3.7.

What can be seen is that there is still some noise even though the mote is in complete rest. The inaccuracy of the gyroscope data deviates ±0.5DPS, the acceleration data ±0.05G and the magnetic data ±0.05GS. Since the gyroscope can measure up to 2000DPS, the acceleration up to 16G and the magnetic up to 12GS this deviation is only a small percentage of the total. This deviation is due to the high measuring range.

What can be seen is that the y-data from the acceleration should measure the earth’s acceleration, which is equal to ≈9.806 m/s². In order to achieve this, the normalization factor was determined so that the value of acceleration in rest was equal to 1.0G which is 9.806 m/s².

The gyroscope data lies around 0 with some small negligible noise. The magnetic data measures the earth’s magnetic field dominantly in the y-direction, but also in the x and z-direction. This is because the earth’s magnetic field is not a vertical vector.
3.1.4. Gyroscope

The gyroscope was calibrated with a spinning mote experiment. The gyroscope can measure up to 2000 DPS, which means when it goes over this amount the peak flattens out. The data in figure 3.8 shows the peak of the spinning motion around the z-axis.

![Gyroscope data](image)

Figure 3.8: Spinning mote experiment

Here the spinning motion of the mote was executed and between 5 and 80 seconds the z-data shows that the peak is flatted out at 2000 DPS. When comparing this to the magnetic data at 8s (see figure 3.9), a total of 6 spins (peaks) can be seen over a time period of 2s which is ≈1080 DPS. When looking at the same data at 14s (see figure 3.10), a total of 12 spins can be seen over a time period of 2s which corresponds to ≈2160 DPS which is just above the measuring range of the device (just like in figure 3.10). This confirms that the gyroscope is correctly calibrated.

![Magnetic data at 8s](image)

Figure 3.9: Magnetic data at 8s

![Magnetic data at 14s](image)

Figure 10: Magnetic data at 14s
3.1.5. Magnetic

The magnetic field measurement was calibrated using a pendulum movement. The results from this measurement are displayed in figure 3.11.

The magnetic data of this measurement as well as the orientation of the mote in the pendulum is shown in figures 3.12 and 3.13, respectively.

Figure 3.12: Magnetic data pendulum experiment

What can be seen from both the graph and the illustrated orientation is that the x-data will measure most difference in magnetic field, because its orientation changes the most with respect to the earth’s magnetic field (the pendulum was given a swing in the x-direction).

Because of this, formula 3.1 was fitted over the results from the x-direction in magnetic data.

\[ f(x) = e^{-x\gamma} A \sin(\omega x - \alpha) \]

Formula 3.1: Fitted formula over pendulum results[11]

Figure 3.13: Orientation of the mote in the pendulum
Here $\gamma$ is the damping ratio, $A$ is the amplitude, $\omega$ is the undamped angular frequency of the oscillator and $\alpha$ is the phase determining the starting point of the wave[12]. Using Matlab, this results in the fit as seen in figure 3.14 with values for the components displayed in table 3.1.

<table>
<thead>
<tr>
<th>$\gamma$</th>
<th>0.1201</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>0.4009</td>
</tr>
<tr>
<td>$\omega$</td>
<td>-5.4690</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>-0.8323</td>
</tr>
</tbody>
</table>

Table 3.1: Fit results components

The fit does not perfectly cover the measured data, but this can be due to the swing not being perfectly in one direction causing additional energy loss which is not considered in the used equation.

### 3.2. Collisions

Here the mote was dropped on different surfaces with different kinds of hardness: metal (figure 3.15), wood (figure 3.16), floor (figure 3.17), plastic (figure 3.18), pillow (figure 3.19), foam (figure 3.20) and water (figure 3.21). In every graph the first bump is displayed:

![Figure 3.14: Fitted curve over magnetic x-data](image)

**Figure 3.14: Fitted curve over magnetic x-data**

**Figure 3.15: Collision with metal**

**Figure 3.16: Collision with wood**

**Figure 3.17: Collision with floor**

**Figure 3.18: Collision with plastic**
The intensity of the peaks cannot be quantified very precisely because the motes do not measure in a high enough frequency to completely measure the whole collision peak. However the time length of these peaks do tell us something about the elasticity of the surface, which can be interesting for distinction between hard and soft collisions. The length of the different collision peaks is displayed in figure 3.22.

The collisions last varying from order $10^{-3}$ to $10^{-1}$s, depending on the hardness and elasticity of the surface. This can be used to identify hard/soft collisions i.e. walls and/or bubbles. What also stands out is that for metal, wood and floor the peaks are very sharp and switch from positive to negative and vice versa. For materials more soft/elastic the peak turns smoother and the acceleration and deceleration become longer. This can be used as a distinction between hard and soft collisions.

![Acceleration data pillow](image1)

![Acceleration data foam](image2)

![Acceleration data water](image3)

**Figure 3.19:** Collision with pillow

**Figure 3.20:** Collision with foam

**Figure 3.21:** Collision with water

The collisions last varying from order $10^{-3}$ to $10^{-1}$s, depending on the hardness and elasticity of the surface. This can be used to identify hard/soft collisions i.e. walls and/or bubbles. What also stands out is that for metal, wood and floor the peaks are very sharp and switch from positive to negative and vice versa. For materials more soft/elastic the peak turns smoother and the acceleration and deceleration become longer. This can be used as a distinction between hard and soft collisions.

![MATERIAL VS. BOUNCE TIME](image4)

**Figure 3.22:** Bounce time lengths for different materials
4. Application in multiphase media

4.1. Single bubble

In order to be able to identify collisions with bubbles a single bubble collision was initiated. To achieve this, the setup sketched in figure 4.1 was used. The orange ball here is the XWM hanging from a thin wire in the fluid environment, demi-water in all cases for this research. The green pipe is where the airflow comes from which then is captured in a small cup attached to a twistable rod, displayed in grey here. The real setup is shown in figure 4.5. When the small cup is filled with air the cup is twisted upside down releasing the entrapped air, which then heads straight to the XWM. The (maximum) bubble volume that is released from the cup is approximately $7 \cdot 10^{-4}$ dm$^3$, which is about $1/40$ of the volume of the XWM itself ($3.1 \cdot 10^{-2}$ dm$^3$).

Figure 4.1: Schematic drawing single bubble setup

Figure 4.2: Data from single bubble collision
Fortunately, the collision with a single bubble does show data in both acceleration and gyroscope, as displayed in figure 4.2. Here two collisions are displayed, one starting at 70s and one starting at 79s. What also can be seen from the magnetic data is that the XWM stays almost in the same preferred configuration (data does barely change so the position with respect to the earth’s magnetic field does not change).

When taking a closer look at the gyroscope data in the x-direction a distinctive signal becomes visible as can be seen in figure 4.3. A sinusoidal wave appears within a sinusoidal wave at the start, both dampening out. What is expected is that the bubbles released from the cup are big enough to be wobbling[13]. This causes the first vibration, whereas the second, longer, vibration is caused by the XWM going back to its preferred orientation. This is because the bubble hits the mote with the dragged water[12] and slides past it, dragging the XWM somewhat upwards. This causes both a translational- (short wavelength) and a rotational (long wavelength) force.

In order to characterize both waves in this single bubble collision the absolute gyroscope data was taken from all three directions. Data was smoothed using a Matlab function and finally a fast Fourier transform (FFT) was carried out on the smooth data. An FFT transfers a period of time into a frequency spectrum[14] (see figure 4.4). Results of this are displayed in figure 4.6. What can be seen from the FFT is that there are dominant frequencies at 1, 2 and 5 Hz. This
is as expected because the low frequencies represent the XWM going back to its preferred orientation and the high frequencies indicate the wave caused by single bubble collisions.

Figure 4.6: Fast Fourier transform of single bubble
4.2. Bubble train

For the next characterization multiple bubble collisions shortly after each other were carried out. To achieve this, the single bubble setup (figure 4.1) was used without the grey cup. A continuous airflow was maintained for a short period of time to see what effect bubble size and collision frequency have. Zoomed in data from this experiment are shown in figure 4.7, showing results from two different airflows. The first airflow is from 230 to 260s, and the second one is from 260 to 290s. What can be seen from the start of each airflow are peaks in the gyroscope data of about 150 DPS. This characterizes the start of an increase in airflow because the valve had an overshoot. Exact airflows remain unknown because no flowmeter was used. Also intensity of peaks changes once the airflow increases. Here, again, an FFT was done for both flowrates as can be seen in figure 4.8. What immediately stands out is that the amplitude of the FFT of flowrate 2 is much higher than the one of flowrate 1. This is due to the collision impact being higher (larger bubbles drag more moving water) resulting in higher peaks in the gyroscope data. Frequencies are as expected at around 3-4 Hz, which is also confirmed when looking at the gyroscope data and determining the frequency by hand (≈20 peaks/5s which is 4 Hz).

Figure 4.7: Data bubble train

Figure 4.8: FFT of both flowrates bubble train
4.3. Bubble column

For the last characterization the XWM was placed in a bubble column (diameter = 18 cm, height = 50 cm, liquid level = 30 cm) and flowrate was increased from 0-100 L/min with steps of 20 L/min. Results are displayed in figure 4.9.

The 5 different regimes can be clearly distinguished with flowrates of 0 L/min in between. 20 L/min starts at 30 and ends at 110s, 40 L/min is from 130-220s, 60 L/min from 250-340s, 80 L/min from 370-460s, and 100 L/min is from 490-550s. For an increasing flowrate, peak intensity for gyroscope, acceleration and magnetic field also increases. With an increasing flowrate comes an increasing void fraction. The void fractions, mean absolute gyroscope and mean absolute acceleration at different flowrates are given in table 4.1. These void fractions are determined by taking the height difference between the fluid level at 0L/min and the given flowrate.

<table>
<thead>
<tr>
<th>Flowrate (L/min)</th>
<th>ΔHeight (dm)</th>
<th>Void fraction (dm³)</th>
<th>Mean gyroscope (DPS)</th>
<th>Mean acceleration (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.15</td>
<td>0.4</td>
<td>89.6171</td>
<td>0.9654</td>
</tr>
<tr>
<td>40</td>
<td>0.3</td>
<td>0.8</td>
<td>99.9241</td>
<td>0.9711</td>
</tr>
<tr>
<td>60</td>
<td>0.45</td>
<td>1.1</td>
<td>124.6744</td>
<td>0.9885</td>
</tr>
<tr>
<td>80</td>
<td>0.6</td>
<td>1.5</td>
<td>140.0510</td>
<td>1.0024</td>
</tr>
<tr>
<td>100</td>
<td>0.65</td>
<td>1.7</td>
<td>156.9801</td>
<td>1.0121</td>
</tr>
</tbody>
</table>

Table 4.1: Void fractions, mean gyroscope and mean acceleration for different flowrates
5. Conclusion

The hypothesis stated: “It is hypothesized that the XWMs will be able to distinguish between soft and hard collisions providing information about bubble size, collision frequency and average gas holdup.” Hard and soft collisions can be identified by respectively short wavelengths and a high amplitude versus longer wavelengths and smaller amplitudes in the gyroscope and acceleration data. When the mote is calibrated correctly the data can tell a lot about certain specific movements and collisions which we are interested in.

When looking at the results of the XWMs in multiphase media some distinction can already be made in flowrates, as showed in the bubble train experiment. With higher flowrates gyroscope and acceleration show peaks with higher amplitudes. It is hard to say anything about bubble size because that cannot be easily correlated to air flowrate or average gas holdup. However, intensity of the collision signal can be taken into account to give an estimation of bubble size.

XWMs have a potential to describe fluid dynamics in multiphase media but still a lot more needs to be characterized. XWMs are not able to measure things like pH, temperature or exact location which can be very useful in bubble columns or other applications. Due to lack of information a validation for CFD is not in place yet, but results look promising enough to continue with characterizing multiphase media with XWMs.

It is recommended to continue with XWMs in multiphase media. For the XWMs itself the following things would be interesting to implement: temperature meter, pH meter, smaller mote size and an ultrasound transmitter to track exact location. This would provide more interesting data for bubble columns. An FFT from the bubble column results may also be interesting because that might make it possible to characterize different regimes.

Nomenclature

**Letters**

<table>
<thead>
<tr>
<th>Letter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Amplitude</td>
</tr>
<tr>
<td>α</td>
<td>Phase</td>
</tr>
<tr>
<td>γ</td>
<td>Damping ratio</td>
</tr>
<tr>
<td>ω</td>
<td>Undamped angular frequency of the oscillator</td>
</tr>
</tbody>
</table>

**Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>XWMs</td>
<td>Xploring WiseMotes™</td>
</tr>
<tr>
<td>IMU</td>
<td>Internal Measurement Unit</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>PA 12</td>
<td>Poly-amide 12</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
</tbody>
</table>

**Units**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPS</td>
<td>Degrees per Second [°/s]</td>
</tr>
<tr>
<td>G</td>
<td>Gravitational acceleration [m/s²]</td>
</tr>
<tr>
<td>GS</td>
<td>Gauss [10⁻⁴T]</td>
</tr>
<tr>
<td>s</td>
<td>Seconds [s]</td>
</tr>
<tr>
<td>Hz</td>
<td>Frequency [Hz]</td>
</tr>
<tr>
<td>T</td>
<td>Magnetic flux density [T]</td>
</tr>
<tr>
<td>Wh</td>
<td>Work [Wh]</td>
</tr>
<tr>
<td>m</td>
<td>Distance [m]</td>
</tr>
<tr>
<td>g</td>
<td>Weight [g]</td>
</tr>
</tbody>
</table>
Acknowledgements

The author would like to thank S.S. Kamath for his direct accompaniment, dr. ir. K.A. Buist for his help and supervisory deeds, prof. dr. H.J. Wörtche for the possibility to work with the XWMs and for his help analyzing data and prof. dr. ir. J.A.M. Kuipers for giving the opportunity to work in his research group.

Bibliography


Appendix A: Matlab script

%% This script transfers raw data into graphs
Data = load ('259-022.mat');
Data = struct2cell(Data);
Data = Data{1, 1};
Data = table2array(Data);
Time = Data(:, 1);

%% Multipliers to normalize values
Gyro_mult = 0.061035;
Acc_mult = 0.0006959498;
Magn_mult = 0.000366;

%% Assigning data to parameters and normalizing data
Gyro_x = Data(:,2)*Gyro_mult;
Gyro_y = Data(:,3)*Gyro_mult;
Gyro_z = Data(:,4)*Gyro_mult;
Acc_x  = Data(:,5)*Acc_mult;
Acc_y  = Data(:,6)*Acc_mult;
Acc_z  = Data(:,7)*Acc_mult;
Magn_x = Data(:,8)*Magn_mult;
Magn_y = Data(:,9)*Magn_mult;
Magn_z = Data(:,10)*Magn_mult;

%% Pre-allocating with surreal values so they can be deleted easily later
Gyro_xM = 500000*ones(length(Time),1);
Gyro_yM = 500000*ones(length(Time),1);
Gyro_zM = 500000*ones(length(Time),1);
Acc_xM  = 500000*ones(length(Time),1);
Acc_yM  = 500000*ones(length(Time),1);
Acc_zM  = 500000*ones(length(Time),1);
Magn_xM = 500000*ones(length(Time),1);
Magn_yM = 500000*ones(length(Time),1);
Magn_zM = 500000*ones(length(Time),1);

%% Setting initial value for M and N
M = 1;
N = 1;

%% In this loop data in the same timestep is merged
for i = 2:length(Time)-1
    if Time(i+1, 1) == Time(i, 1)
        N = i+1;
    else
        Gyro_xM(i) = mean(Gyro_x(M:N));
        Gyro_yM(i) = mean(Gyro_y(M:N));
        Gyro_zM(i) = mean(Gyro_z(M:N));
        Acc_xM(i)  = mean(Acc_x(M:N));
        Acc_yM(i)  = mean(Acc_y(M:N));
        Acc_zM(i)  = mean(Acc_z(M:N));
        Magn_xM(i) = mean(Magn_x(M:N));
        Magn_yM(i) = mean(Magn_y(M:N));
        Magn_zM(i) = mean(Magn_z(M:N));
        M = i+1;
    end
    if Time(i,1) ~= Time (i-1,1) && Time(i,1) ~= Time (i+1,1)
        Gyro_xM(i) = Gyro_x(i);
        Gyro_yM(i) = Gyro_y(i);
    end
end
Gyro_zM(i) = Gyro_z(i);
Acc_xM(i) = Acc_x(i);
Acc_yM(i) = Acc_y(i);
Acc_zM(i) = Acc_z(i);
Magn_xM(i) = Magn_x(i);
Magn_yM(i) = Magn_y(i);
Magn_zM(i) = Magn_z(i);
M = i+1;
end
end

%% This loop makes sure there is 1 point for each timestep
for i = 2:length(Time)-1
    if Time(i+1, 1) == Time(i, 1)
        Time(i, 1) = 0;
    end
end

%% Irrelevant data is deleted
Time(1)   = 0;
Time(end) = 0;
Time(Time==0) = [];
Gyro_xM(Gyro_xM==500000) = [];
Gyro_yM(Gyro_yM==500000) = [];
Gyro_zM(Gyro_zM==500000) = [];
Acc_xM(Acc_xM==500000) = [];
Acc_yM(Acc_yM==500000) = [];
Acc_zM(Acc_zM==500000) = [];
Magn_xM(Magn_xM==500000) = [];
Magn_yM(Magn_yM==500000) = [];
Magn_zM(Magn_zM==500000) = [];

%% Setting time value from #iterations to seconds
Time = Time - Time(1);
ItperSec = 1029.166666;
Time = Time / ItperSec;

%% Data is merged for easy saving
DataM = [Time, Gyro_xM, Gyro_yM, Gyro_zM, ...
        Acc_xM, Acc_yM, Acc_zM, Magn_xM, Magn_yM, Magn_zM];

%% Data is plotted
figure(1)
subplot(3,1,1)
plot(Time, Gyro_xM, Time, Gyro_yM, Time, Gyro_zM)
title('Gyroscope data')
xlabel('Time (s)')
ylabel('Gyro (DPS)')
legend('x', 'y', 'z')
grid on

subplot(3,1,2)
plot(Time, Acc_xM, Time, Acc_yM, Time, Acc_zM)
title('Acceleration data')
xlabel('Time (s)')
ylabel('Acceleration (G)')
legend('x', 'y', 'z')
grid on

subplot(3,1,3)
plot(Time, Magn_xM, Time, Magn_yM, Time, Magn_zM)
title('Magnetic data')
xlabel('Time (s)')
ylabel('Magnetic (GS)')
legend('x', 'y', 'z')
grid on
Appendix B: Other performed experiments

Experiment 1: Spinning mote

![Data spinning motion](image)

In this experiment the mote was given a spinning motion while hanging from a wire, and that can be seen from the data plotted in figure B.1. This was done so that the mote could only spin in one direction, with the spin axis being the z-axis. The spinning motion was initiated by firstly spinning the mote in one direction so that the wire would initiate the spin. This was done before measuring. Then the mote was turned on and let go which caused the spinning motion. Firstly an acceleration can be seen around 2s (the initial three taps), followed by a spin that lasts from 5 till 80s. A zoom on the gyroscope data during the spin is given in figure B.2.
What can be clearly seen is that the mote starts spinning at around 5 seconds, as it starts building up DPS in the z-axis. Just after 10s the IMU has reached its maximum capacity of measuring DPS, so the peak flattens out. The z-direction however, behaves different from the x- and y direction. This is because the spinning motion is around that axis.

The magnetic data also tells us something about the three spinning motions because it measures the earth’s magnetic field. The orientation of the mote changes all the time during the spinning motion which changes the way the mote measures the earth’s magnetic field so this explains the results in the magnetic data. From the magnetic data spins can easily be verified because a sinus like wave represents the spinning motion as seen below (one spin is one period because the orientation with respect to the earth’s magnetic field is at the starting point again then). Data at 14s is shown (where the mote has a spin of 2000 DPS) in figure B.3, and the DPS can also be verified from the magnetic data by counting the number of spins multiplied by 360° (one spin) divided by the time span of the number of spins as seen in the following equation: 

\[
DPS = \frac{\text{#spins} \times 360^\circ}{\text{timespan}}
\]

Which is in this case: 

\[
DPS = \frac{12 \times 360}{2} \approx 2160 \text{ DPS}
\]

which confirms the gyroscope data.

\[\text{Figure B.2: Zoom on the gyroscope data of the spinning mote}\]

\[\text{Figure B.3: Magnetic data spinning mote}\]
In this experiment the mote was given a rolling motion over a smooth surface for three times. What stands out in figure B.4 first are the three oscillations in the magnetic data at the following time intervals: 3-5s, 6-8s and 10-12s; this is where the mote has a rolling motion (it responds to the earth magnetic field). This rolling motion can also be seen in the acceleration data in the form of clustered peaks due to bumps during rolling (the mote is not completely round) and in the gyroscope data in the same timeframes. The last things that are obvious here are the peaks in the acceleration data at 2, 5, 9 and 13s. These are the taps on the table to indicate a (new) experiment.
Experiment 3: Dropping the mote on the floor

If we correlate the gyroscope, acceleration and magnetic data from figure B.5 the taps used to indicate a (new) experiment can be identified. These lie around 2, 7, 11 and 15s (triple tap, then double, double, triple). What also can be seen is the mote bouncing on the floor and rolling away with the peaks in acceleration around 4.5s followed by a short rolling motion in the gyroscope. This pattern repeats itself at 9s and 13s. Also the air time can be seen, which is where the acceleration of all three axis is equal to 0. The mote falls with the acceleration of the earths making it measure no net acceleration.
Experiment 4: Rolling the mote on a flat surface followed by a free fall

This experiment is a combination of the previous two experiments so the results can be coupled. Results are displayed in figure B.6. The mote was given a rolling motion on a flat surface, followed by a free fall for three times. The start and end taps of this experiment can be identified very easily, namely at around 1.5 and 17.5s. One intermediate tap is at 13s and the other one should be around 9s, but it merges with the rolling motion. The second try (from 8 to 11s) will be elaborated and is shown in figure B.7.
In both the magnetic data and the acceleration data a sinusoidal wave can be observed. However, this wave stops in the acceleration data at 9.5s while in the magnetic data it goes on until 9.8s and then obtains a shorter period. The time between the stopping of the peaks in the acceleration and the magnetic data getting a shorter period is the air-time of the mote. This is because the mote still has a spinning motion (the sinusoidal wave in the magnetic data and the raising values for gyroscope data) but it doesn't bump on the surface (the straight lines in acceleration data). This can also be seen from gyroscope data from 9.5 to 9.8s, as these increase linear so that says the increase of spinning motion is not affected by the surface. This is also true because the acceleration data goes to 0 in that timeframe. At around 9.8s the mote hits the ground for the first time, displayed by the intense acceleration peak at 9.8s. Then it immediately starts spinning faster (the shorter period in the magnetic data from 9.8 till 10.5s and the intense peak in gyroscope data after 9.8s), after which it bounces for the second time at 10.25s. The mote starts spinning in another direction (seen in the shift of y-data in both gyroscope and magnetic at 10.25s) and then bounces several times.
Experiment 5: Dropping the mote in a bucket filled with water

In this experiment the mote was dropped in water three times consecutively. Data is shown in figure B.8. A zoom on the important part of the acceleration data is given in figure B.9.

What is seen here is the release of the mote, the air-time of the mote and the collision with water followed by a spin motion. The mote is released at the point the acceleration goes from 1 to 0 G in the y-axis (at 26.1s). Here the mote falls with the acceleration of the earth, making the mote measure no net acceleration. At 26.3s the mote hits the water indicated by the large peak. Then starting from 26.5s the mote gains a spinning motion in the water indicated by the sinusoidal results.