Assessing the influence of sensitivity and frequency on the performance of the Midge

Leon Kempen
Supervisor(s): Hayley Hung, Stephanie Tan, Jose Vargas Quiros
EEMCS, Delft University of Technology, The Netherlands

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Abstract

The Midge is a wearable badge created by the Socially Perceptive Computing Lab, Pattern Recognition and Bioinformatics group of the Delft University of Technology, with as goal to analyse human behaviour. The badge has a digital motion processor (DMP) that can determine its orientation. This DMP makes use of an inertial measurement unit (IMU), that houses an accelerometer, a gyroscope and a magnetometer, to calculate its movement in a 3D-space. For both of the accelerometer and gyroscope the Full Scale Range (FSR) can be changed, in addition to the frequency. In this paper, the effects of both elements are analysed to determine if they influence the accuracy of the data gathered. The results show that the changing the FSR does not influence the accuracy of neither the two sensors nor the performance of the DMP. On the other hand, it was found that changing the frequency does influence the performance of the Midge. Even though the frequency did not affect the measurements of the accelerometer and gyroscope directly, the performance of the DMP was affected. The DMP performed best with a frequency of 150 Hz. Using a higher frequency also captured local extremes and turning points from the sensors and the interpreted orientation more precisely.

***Keywords*—** DMP, IMU, FSR, Quaternions

1 Introduction

Standard modern phones have around fourteen different sensors [1]. These sensors can measure data like the heart rate of the user, to say something about the health of the user; the amount of ambient light to determine whether a flash should be used whilst taking a photo; and movement in a three dimensional space to estimate in which direction the user is moving. However incorrect or inconsistent data could lead to unwanted side-effects, which are potentially dangerous. Therefore it is important that the collected data is correct, otherwise the sensor would be useless and could be harmful for the user, such as [2] and [3].

The Midge is a wearable badge with several sensors, created by the Socially Perceptive Computing Lab, Pattern Recognition and Bioinformatics group of the Delft University of Technology. The Midge is designed to analyse human behaviour in social settings. One of components of this badge is the Digital Motion Processor (DMP) which creates a rotation vector in the form of an quaternion based on the measurement of an inertial measurement unit (IMU). The quaternion can be used to determine the orientation of the badge in a three dimensional field. The IMU uses three internal sensors to measure the movement of the badge, namely the magnetometer, the gyroscope and the accelerometer. The values are interpreted by the DMP to a quaternion with a sensor fusion algorithm.

Earlier research [4] has shown that the Midge has an accuracy that is comparable to a phone, however the impact of the Full Scale Range (FSR) has not been taken into account. Two of the three sensors used by the IMU have a FSR that can be changed. The accelerometer has an programmable FSR in the ranges ± 2, ± 4, ± 8 and ± 16 measured in g, relative to the force of gravity, and the gyroscope has ranges ± 250, ± 500, ± 1000 and ± 2000 measured in degrees per second (DPS). For both sensors it holds that the smaller the FSR value is, the higher the sensitivity becomes [5]. However, when the sensitivity is too high, values might be cut off. In other words, if the value is greater than the limit, the measured value will be equal to the limit.

Another way to increase the accuracy of the Midge, is to change the data rate of the IMU. When the data rate is higher, more measurements will be used by the DMP and stored in the memory of the Midge, which will thus require more memory. Santoyo-Ramón et al. [6] had shown that the increase in measurement points is not always worth the trade-off. It was shown that the sensor they used could correctly identify if it should take action with a measurement rate of 20 Hz, whereas one of 140 Hz was possible. Furthermore, the study points out that a higher frequency can also introduce the problem of oversampling, resulting in a decline of accuracy of the sensor.

This research is focused on the influence of the data rate of the IMU and the FSR values of the Midge on the performance of the sensors and DMP in terms of accuracy. In order to assess these effects, the IMU and DMP of the Midge are compared to a high-end IMU of xSens [7]. The comparison is based on both the raw measurements from the sensors and the interpreted quaternions of the DMPs.

This paper first describes the relevant background information regarding the IMU and the FSR. After that the methodology is discussed in-depth followed by the results, discussion, responsible research and the conclusion.

2 Background

In order to get a better understanding of the capabilities of the Midge, it is important to know how an inertial measurement unit (IMU) works and what influence the Full Scale Range (FSR) has on the measurements.

Inertial Measurement Unit

An IMU makes use of three sensors, namely the accelerometers, the gyroscope and the magnetometer to determine its movement and orientation [8]. The measurements of these sensors are combined with a sensor fusion algorithm in the Digital Motion Processor.

The accelerometer and the gyroscope measure the acceleration and the angular velocity respectively. Both sensors measure in three dimensions, namely the x, y and z-axis. With these measurements the IMU can determine linear acceleration, pitch, roll and yaw. The magnetometer measures the change in gravitational force and is used to calibrate the other sensors.

However the magnetometer has one major drawback, since its measurements can be influenced by other magnetic fields [9]. Therefore, other magnetic materials and nearby electronic devices can affect the data gathered by this sensor. Since the magnetometer is used to calibrate the accelerometer and gyroscope, these external factors can also influence these sensors.

For the Midge, the reporting frequencies of the separate sensors also differ [10]. The accelerometer and gyroscope have a reporting frequency up to 225 Hz, whereas the magnetometer is limited to 70 Hz. The frequency used by the Midge cannot be set for each sensor individually, but when it is set to a value greater than the limit, the maximum frequency is used.

The frequency used can be changed through the Hub-code of the Midge [11]. Increasing the data rate of the Midge, increases the number of measurements stored on its SD-card. The maximum number of measurements is also limited by the frequencies of the sensors. For the DMP a minimum of 50 Hz is needed to create a quaternion [10].

Full Scale Range

The FSR defines the minimum and maximum value that a sensor can digitally output to the analog-to-digital converter (ADC) [12] and is therefore hardware specific. The ADC can only output a set number of unique values, depending on the number of bits. For example, an 16 bit ADC can represent 65536 (2^{16}) numbers. This number is used to divide the range into equal steps and measurements will be rounded to the closest value.

The smaller the FSR is, the more precise the measurements become. With a smaller FSR it would therefore be possible to measure more subtle movements. However, it is not possible to measure values outside of the range. If the value would be greater than the range, the output value is the maximum of the range.

Like the data rate, the FSR can be changed through the Hub-code [11]. Since the FSR is hardware specific only a limited number of options are available. For the accelerometer the possible values are ± 2, ± 4, ± 8 and ± 16 measured in g (relative to gravity) and for the gyroscope ± 250, ± 500, ± 1000 and ± 2000 measured in DPS (degrees per second) [5].The FSR of the magnetometer cannot be changed.

3 Methodology

After the frequency range and different FSR settings were identified an experiment to gather data of the Midge was designed. Once the data was gathered, the data is compared to an high-end Xsens IMU MTi-100 [7].

Experimental

For the experiment it was important that the Midge would be tested in multiple degrees of freedom. The research of Engbers [4] focused mainly on the x axis, however this does not completely reflect the actual use case of the Midge.

The first experiment thought of to assess the performance of the IMU and DMP of the Midge incorporated the use of a robotic arm. The robotic arm would be able to repeat the same movement multiple times with high precision. However, the robotic arm that was available would require a motion capture system to track the movement of the Midge. This would make the setup complex and out of scope.

Mourcou et al. [13] have shown that the IMU of a modern phone is comparable to one of a (higher end) robotic arm or a high-end IMU used for clinical research. For an experiment, the Midge and a phone could be strapped together and used to measure movement. The trade-off for this would be the loss the repeatability of the robot arm. Since the use-case of the Midge is to be worn by humans, it was decided to research its performance on human-like motion in which the repeatability of the movement was not essential. For gathering the movement of the phone the application PhyPhox would be used. Nonetheless, there was also a downside of PhyPhox, namely that the application does not export the quaternions.

Additionally, the same study [13] also found that the measurement algorithms of the phones cannot follow movements with a high angular velocity, like over 90 DPS for a very short time. Such movement, however, is possible to happen during human motion.

Another advantage of human movement, was that the motion could be more complex. This movement is also used for validating IMUs in general, like [14] [15]. The IMUs would then be validated with an optical motion capture systems. The goal of this research was not to validate the IMU of the Midge, but to analyse the effect of the FSR and the frequency on the accuracy. Therefore another proven reliable IMU, like the Xsens IMU, would suffice.

The human would hold two Midges and the Xsens IMU that were strapped together. During the experiment the same movement was executed for two different FSR settings and several output rate frequencies. The FSR settings chosen were the second smallest option and the maximum option. The reason for this is that setting the range too small, could lead to many cut-off values, which would influence the results significantly. By using the second smallest option, measurements twice as large as the smallest option could be measured, while the range is four times smaller than the maximum value.

(a) Top view

(b) Side view

Figure 1: Xsens IMU strapped to two Midges

Figure 2: The way the Xsens and Midges were held during the experiment

For the frequencies 50, 100, 150, 200 and 250 Hz were used. The value of 50 Hz corresponds with the lowest reporting rate [10], whereas the 250 Hz is slightly above the maximum rate of 225 Hz.

The case of the Midges is like the Xsens IMU rectangular and roughly the same length and width (Figure 1). Therefore they could be stacked together easily. The only downside was that the IMU of the Xsens would then be turned 90 degrees compared the one of the Midges. Therefore the x-axis of the Midge corresponded towards the negative y-axis of the Xsens IMU. However this was resolved when parsing the data into a program to compare the results, assigning the x values of the Xsens measurements to its y values and the negated y values to the x values.

The movement chosen for this experiment was the dance of the Macarena. This dance is simple to learn and features all three rotations needed to test, namely pitch, roll and yaw. During this movement the Xsens and Midges were held in the fingers of the left hand as seen as in Figure 2. Since the Xsens IMU required to be cabled, this grasp allowed for free movement of the hand without risking to damage the cable. As mentioned earlier, the dance movements were repeated several times to get more reliable measurements. Each combination of FSR setting and sample rate was repeated three times. After which the Midges would be updated to set the new settings.

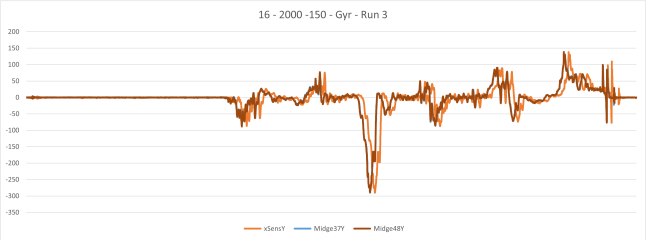

Figure 3: Measurements before finding the right time offset

Result Assessment

After the data had been gathered, the results of the Midges sensors are compared to the measurements of the Xsens IMU. Both the raw values, namely the measurements of the separate sensors, and the interpreted values, the resulting quaternion, are considered. In this experiment the data of the Xsens is seen as ground truth. By the assessment of the raw values, every axis is compared separately to the measurements of the Xsens on the basis of the Mean Squared Error over all corresponding timestamps. This is because a lower data rate of the Midge results in less measurements than the data of the Xsens IMU provides. To analyse the quaternions, the MSE is also used. This is done over the x, y and z values of the quaternion.

4 Results

After the experiment was recorded, the data had to be parsed and converted to use the same units. The gyroscope of the Xsens IMU outputted the change in angles in radians per second, whereas the Midge uses degrees per second. Therefore the radians where recalculated to degrees.

Another difference in units was found in the accelerometer. The accelerometer of the Xsens IMU measures the acceleration in term of meters per seconds squared and the Midge in g. To make the data comparable, the output of the Xsens IMU was divided by the gravitational constant.

Additionally, the Xsens outputted the quaternions in a different order of magnitude compared to the Midge. However, since quaternions are unit-less they could not be converted or scaled easily. For the comparison the MSE was still used to asses the performance of the DMP of the Midge.

While performing the experiment, the Midges were inconsistent in recording correctly. In some cases the Midges would not connect to the hub properly, sensors could not be started or the recording would not be terminated at all. This lead to some faulty recordings and missing data from runs. In order to compensate for this, several runs were redone. For every combination of FSR and frequency at least two successful runs per Midge were used.

Another issue that arose was the slight difference in timestamps. Since multiple devices were used to measure the data, the timestamps of the Midges and the Xsens IMU were not synchronised. As can be seen in Figure 3, the graphs of the measurements have the same shape, but the measurements of the Midge are shifted to the right.

Even though both machines, one Windows machine to connect to the Xsens IMU and one Linux machine to serve as Hub for the Midges, were set to use the same network time protocol (NTP), This offset was not consistent over the different runs. Therefore the timestamp of the measurements of the Midge were increased slightly until the MSE of the gyroscope converged to its lowest value. This resulted in more synchronised measurements and overlapping graphs, like Figure 4.

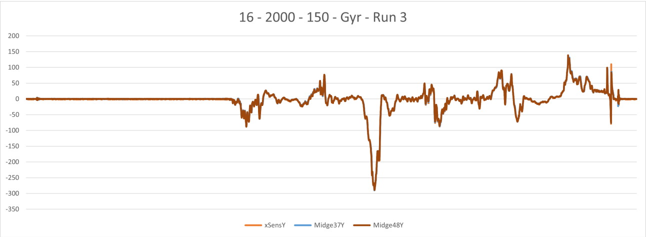

Figure 4: Measurements after finding the right time offset

Acc	Hz	MSE x	MSE y	MSE z
4	50	0.002	0.001	0.001
4	100	0.003	0.001	0.004
4	150	0.006	0.002	0.005
4	200	0.002	0.001	0.006
4	250	0.001	0.001	0.002
16	50	0.005	0.002	0.005
16	100	0.001	0.001	0.002
16	150	0.002	0.001	0.001
16	200	0.001	0.000	0.001
16	250	0.012	0.003	0.006

Table 1: Mean Squared Error of the accelerometer of Midge 37

Acc	Hz	MSE x	MSE y	MSE z
4	50	0.005	0.002	0.002
4	100	0.004	0.002	0.005
4	150	0.008	0.005	0.010
4	200	0.005	0.005	0.010
4	250	0.004	0.003	0.002
16	50	0.005	0.002	0.010
16	100	0.004	0.003	0.006
16	150	0.002	0.002	0.003
16	200	0.003	0.002	0.003
16	250	0.004	0.001	0.003

Table 2: Mean Squared Error of the accelerometer of Midge 48

Tables 1 and 2 display the averaged Mean Squared Error over the runs with the different combinations of the FSR of the accelerometer and frequencies. From these tables it can be seen that the averaged MSE over the runs is relatively consistent. This shows that accuracy of the accelerometer does not change when the report rate and range change.

Tables 3 and 4 display the averaged Mean Squared Error over the runs with the different combinations of the FSR of the gyroscope and frequencies. In contrast to the accelerometer the MSE of the measurements of the gyroscope fluctuate more. For both Midges, the MSE is high with the FSR of ± 500 DPS and frequency settings of 150 and 200 Hz However for the combinations of ± 500 DPS and 250 Hz, and ± 2000 DPS and 50 Hz the MSE of Midge 37 is significantly lower compared to Midge 48.

Tables 5 and 6 display the averaged Mean Squared Error of the quaternions over the runs with the different combinations of the FSR of the accelerometer and gyroscope, and frequencies. For both the Midges, the MSEs of the y and z values seem related. For each com-

Gyr	Hz	MSE x	MSE y	MSE z
500	50	7.29	8.67	6.60
500	100	6.21	6.16	3.99
500	150	9.13	12.00	8.09
500	200	11.25	12.52	7.82
500	250	4.95	6.77	6.57
2000	50	3.81	3.00	6.33
2000	100	2.99	4.87	2.42
2000	150	3.99	3.82	2.82
2000	200	4.97	3.24	2.63
2000	250	5.10	5.65	5.47

Table 3: Mean Squared Error of the gyroscope of Midge 37

Gyr	Hz	MSE x	MSE y	MSE z
500	50	4.86	6.39	8.44
500	100	6.28	5.44	8.41
500	150	16.27	19.01	15.38
500	200	21.75	17.17	11.90
500	250	11.39	8.65	10.08
2000	50	38.56	63.80	36.77
2000	100	8.92	11.76	7.57
2000	150	4.30	4.45	5.29
2000	200	9.10	6.93	10.41
2000	250	5.59	6.91	5.43

Table 4: Mean Squared Error of the gyroscope of Midge 48

Acc	Gyr	Hz	MSE x	MSE y	MSE z
4	500	50	0.6686	0.2170	0.2172
4	500	100	1.3035	0.2314	0.2315
4	500	150	0.5452	0.1737	0.1740
4	500	200	2.0503	1.1427	1.1429
4	500	250	2.8344	0.1844	0.1847
16	2000	50	0.2407	1.9444	1.9447
16	2000	100	1.5593	0.2419	0.2421
16	2000	150	3.1653	3.0247	3.0248
16	2000	200	0.5476	0.0989	0.0990
16	2000	250	0.6160	0.1703	0.1706

Table 5: Mean Squared Error of the quaternions of Midge 37

Acc	Gyr	Hz	MSE x	MSE y	MSE z
4	500	50	0.1451	0.0945	0.0947
4	500	100	0.1161	0.1173	0.1175
4	500	150	0.1115	0.1040	0.1042
4	500	200	0.1254	0.2327	0.2328
4	500	250	0.5193	0.1734	0.1746
16	2000	50	2.4556	0.1828	0.1830
16	2000	100	2.8883	0.1453	0.1454
16	2000	150	0.1423	0.0929	0.0929
16	2000	200	0.6593	0.1589	0.1592
16	2000	250	0.2893	0.1634	0.1636

Table 6: Mean Squared Error of the quaternions of Midge 48

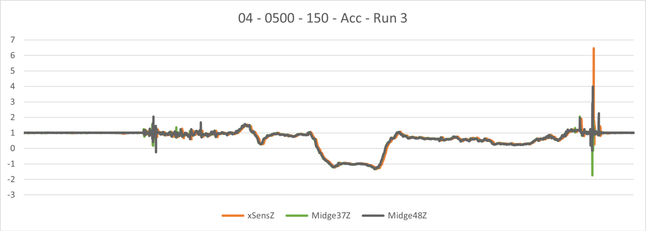

Figure 5: Cut off value on Accelerometer

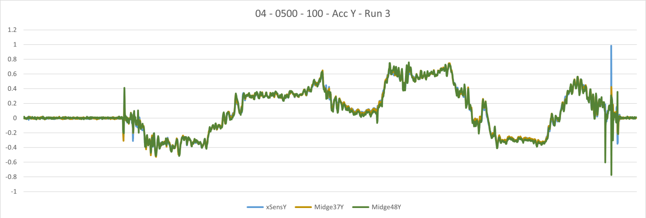

Figure 6: Incorrect Midge measurements on sudden movement

bination of FSR and frequency the MSE of the y values is slightly lower or equal to the MSE of the z values.

Table 5 shows that the MSE of the quaternions is low, when the FSR is larger and the frequency is high. For the smaller FSR range the MSE of the quaternions of Midge 37 is low when the frequency is equal to 150 Hz for all three values, or when the frequency is 250 Hz for the y and z values.

The MSEs of Midge 48 (Table 6) are more consistent over the runs, with two outliers of the x values in the high FSR and frequencies 50 and 100 Hz. In both the smaller and the larger FSR the frequency of 150 Hz resulted in the lowest MSE averaged over the x, y and z values.

Comparing the tables 1, 2, 3 and 4 to 5 and 6 shows that a higher MSE in the measurements of the sensor does not imply that the MSE of the resulting quaternions is also high. Therefore, having relatively inaccurate measurements of the sensors, does not necessarily make the quaternions inaccurate. For example the combination of the FSR ± 4 g for the accelerometer, ± 500 DPS for the gyroscope with a frequency of 150 Hz has a relatively high MSE for the measurements of the accelerometer and the gyroscope, yet the MSE of the resulting quaternions is the lowest of the smaller FSRs of Midge 37.

During the measurements, the majority of the measurements remained within the set FSR. However in some cases, like the one in Figure 5, measurements were cut off. This occurred with measurements in both the accelerometer and gyroscope.

Another effect that is not shown in the tables is that a higher frequency captures fast movement better. Given that the MSE only measures the error on the timestamps of the Midge, it does not take the movement between the two measurements into account. For example, when a frequency of 50 Hz is used, there is roughly 20 milliseconds between the measurements. If there is a local extreme between those measurements, it will not be captured.

Finally, in some cases a quick change in movement resulted in incorrect measurements of the Midge. As Figure 6 shows, the last part of the movement shows a peak of Midge 48 in the incorrect direction even though the rest of the graph overlaps with the Xsens IMU and the other Midge.

5 Responsible Research

This section discusses any ethical implications regarding the research and experiment of this project. It is important that the experiment used for the research is safe and reproducible. In section 3 the methodology of the experiment is described step by step. However due to the nature of this experiment, it is impossible to reproduce the same data since human movement is never exactly the same. Therefore the experiment was repeated several times. In terms of results of the experiment, it is repeatable.

Another important factor of ethical research is the safety regarding the experiment. For this experiment there are no apparent hazards, the only thing to keep in mind is to have enough space to move freely without hitting anyone or anything in the environment.

The final aspect of responsible research is the possible implications that the research may have. For this research, no data is gathered other than the measurements of the Xsens IMU and the Midge. However, the real world use-case of the Midge is tracking human movement and possibly recording the audio. It is therefore important that the wearers of the Midge are aware of what is being recorded, how and where the data is stored and what will be done with the gathered data.

6 Discussion

The results indicate that there is no correlation between the FSR and the accuracy of the accelerometer and the gyroscope. For the accelerometer the MSEs are consistent and very comparable between the two FSR ranges. This also shows that changing the reporting rate of the sensor does not influence the accuracy of the sensor itself.

The MSE of the gyroscope varies more than the MSE of the accelerometer and has more outliers. Since the outliers can be found in both the smaller and larger FSR, they are not the result of many cutoff values. The higher error of the gyroscope might have the same underlying issue as seen in the IMUs of the phones [13], namely that the IMU becomes less accurate during short movements with a high angular velocity.

The movement chosen might not have been ideal to assess the influence of the FSR on the accuracy of the sensors, since the motion was based on large and relatively fast gestures. During this type of motion the change in precision does not influence the outcome significantly. In order to asses this more in depth, much slower and subtle movement should be used as well. However this type of movement does not reflect the real world use-case of the Midge.

Unlike the change in FSR, the change in frequency does affect the performance of the Midge. For both Midges the lowest averages of the MSE over the x, y and z values are found in the measurements with a frequency of 150 Hz with the exception of the high FSRs of Midge 37, which indicates that the sensor fusion algorithm of the Midge performs best with this frequency.

When the frequency is greater than 150 Hz, the MSE of the quaternions is also greater. This is decrease in performance is comparable to the decrease in accuracy of the fall detection sensors used by Santoyo-Ramón et al. [6] and can thus be a result of oversampling.

On the other hand, using a higher frequency also captures local extremes and turning points better. With these values it is possible to find more subtleties in the graph. Since the Midge is used to analyse human behaviour, these subtleties can for example be certain gestures.

7 Conclusions and Future Work

From the results it can be concluded that the FSR does not influence the performance of the accelerometer and gyroscope of the Midge. In both the smaller and larger FSR ranges, the MSE of the accelerometer is consistent, whereas the MSE of the gyroscope fluctuates with outliers in both the smaller and the larger range.

Additionally, if the accuracy of the accelerometer and gyroscope would increase when setting a smaller FSR it does not increase the performance of the DMP. Since making the FSR smaller would only increase the precision of the measurements, it does not guarantee that the quaternions would also be more precise.

The change in frequency does not influence the performance of the accelerometer and gyroscope either. On the other hand, changing the frequency does influence the performance of the DMP. The results indicate that the sensor fusion algorithm of the DMP performs best at 150 Hz. Having a higher frequency of measurements captures local extremes and turning points better. However using higher frequencies can introduce the problem of oversampling, which would decrease the accuracy of the DMP.

Further research could be done to find out why the MSE of the gyroscope of the Midge fluctuates significantly more than the MSE of the accelerometer. Potentially this is caused by a certain type of high angular velocity. A starting point for this would be test the Midge specifically on this type of movements.

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