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A Magnetometer-based Method for In-situ Syncing of Wearable Inertial Measurement Units

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2 ABSTRACT

3 This paper presents a novel method to synchronise multiple wireless inertial measurement
4 unit sensors (IMU) using their onboard magnetometers. The basic method uses an external
5 electromagnetic pulse to create a known event measured by the magnetometer of multiple IMUs
6 and in turn uses this to synchronise the devices. An initial evaluation using 4 commercial IMUs
7 reveals a maximum error of 40ms per hour as limited by a 25 Hz sample rate. Building on this
8 we introduce a novel method to improve synchronisation beyond the limitations imposed by the
9 sample rate and evaluate this in a further study using 8 IMUs. We show that a sequence
10 of electromagnetic pulses, in total lasting less than 3-seconds, can reduce the maximum
11 synchronisation error to 8ms (for 25 Hz sample rate, and accounting for the transient response
12 time of the magnetic field generator). An advantage of this method is that it can be applied to
13 several devices, either simultaneously or individually, without the need to remove them from the
14 context in which they are being used. This makes the approach particularly suited to synchronising
15 multi-person on-body sensors while they are being worn.

1 INTRODUCTION

16 In the last decade there has been a huge growth in applications for IMU-enabled wearable and IOT devices.
17 Applications stretch from the wider topics of human activity recognition Bian et al. (2022); Bulling
18 et al. (2014) and multi-sensor fusion Gravina et al. (2017), to studies measuring social interaction and
19 engagement in real-world settings, e.g. Sun et al. (2023); Gao et al. (2020). Many such applications require
20 precise synchronisation between separate IMU devices, an issue that is made all the more difficult over
21 longer timescales. For example in Ward et al. (2018), recordings of multiple autistic children and actors
22 performing together over several hours are analysed to uncover fine-grained moments of motion synchrony.
23 Similarly, Gao et al. (2020) records detailed physical and physiological data from students in class over a

24 period of several weeks. In both of these examples, data is recorded offline on individual devices and then
25 uploaded at the end of a session. To perform any time-series analysis or fine-grained fusion of such data,
26 then precise synchronisation between data sources is essential.

27 Most commercial IMUs include an on-board real-time clock (RTC). Unfortunately, typical RTCs tend to
28 drift over time, such that over a long recording duration the clocks across multiple devices will vary wildly.
29 This means that RTC-only based synchronisation is not a viable option for longer experiments.

30 Efforts to overcome the synchronisation problem can be grouped into three categories: network-based,
31 event/gesture-based, or a combination. Much work has been done using Network Time Protocol (NTP)
32 Raman et al. (2020); Wang et al. (2019); Li and Sinha (2012); Yan et al. (2019) and Precision Time Protocol
33 (PTP) Idrees et al. (2020) for time synchrony in IoT, however such protocols have been proven to be noisy
34 with errors exceeding 1800ms or impractical for common mobile sensing task Luo et al. (2017). Moreover,
35 most commercial IMU devices do not have network options requiring external network chips to be included.
36 One solution is to use sync events within the data itself, creating a common signal across different sensors
37 and sensor types to facilitate temporal alignment. Kinetic events are most commonly used requiring the
38 experimenter or participant to make a predefined movement, such as clapping or hitting the table Wang
39 et al. (2019); Ward et al. (2017); Plotz et al. (2012), or even tapping the ear Hoelzemann et al. (2019).
40 Bannach et al. (2009) show that synchronising events can be collected from various sensors, including
41 sound and light sensors. LED-sourced light has been used previously to update clock signals in IoT devices
42 Guo et al. (2016). ECG sensors have also been used to synchronise across wearable devices Wolling et al.
43 (2021a) Wolling et al. (2021b).

44 Electromagnetic fields have been previously used to synchronise wireless sensor networks (WSN). Rowe
45 et al. (2009) developed an LC tank receiver circuit tuned to 60 Hz such that they can use the stochastic
46 nature of the magnetic fields radiating from AC power lines to create a synchronising signal. The method
47 described achieves an average synchronisation error of less than 1 ms. This requires the WSN to be near
48 AC power lines which might limit the use in wearable applications (e.g. when outdoors). Another limitation
49 pointed out by Rowe et al. (2009) is that the system temporarily fails when any objects get within proximity
50 of the LC circuit creating a very strict synchronising environment. Additionally, this method requires
51 adding new hardware to commercial IMU devices.

52 In a recent work most similar to that presented here, Spilz and Munz (2023) demonstrate the use of
53 inductors to create an electromagnetic event which is captured by magnetometers on Shimmer3 IMUs.
54 They are able to achieve sub-sample period accuracy by looking at which transient responses have a sample
55 present. This technique allows them to achieve a 2.6ms offset error using 100Hz magnetometers, requiring
56 a synchronisation time of 8 seconds. The method described is highly dependent on the IMUs being still
57 relative to the inductors, therefore a synchronisation box was developed to hold the IMUs in place. As the
58 method described relies on a sample "hitting" a transient response, the chances of this happening decrease
59 as the sample rate decreases, increasing the synchronisation time proportionately to the decrease in sample
60 frequency. Another limitation of the method is that all the IMUs must be synchronised at the same time
61 meaning experiments are limited to the number of inductors in the synchronisation box.

62 Most of the previous methods, particularly those requiring a kinetic event, can be disruptive often
63 requiring the subjects to stop what they are doing to perform an action or even in some cases transfer their
64 wearable sensors to holders. The method proposed by this paper minimizes these disruptions and replaces
65 them with a wireless solution that requires no new hardware to be added to the commercial IMU devices.

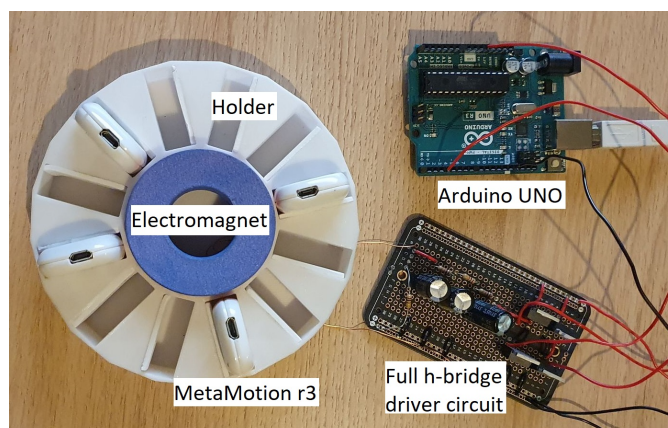


Figure 1. Experimental setup showing a simple 2W EMPG circuit and holder with 4 MetaMotion IMUs

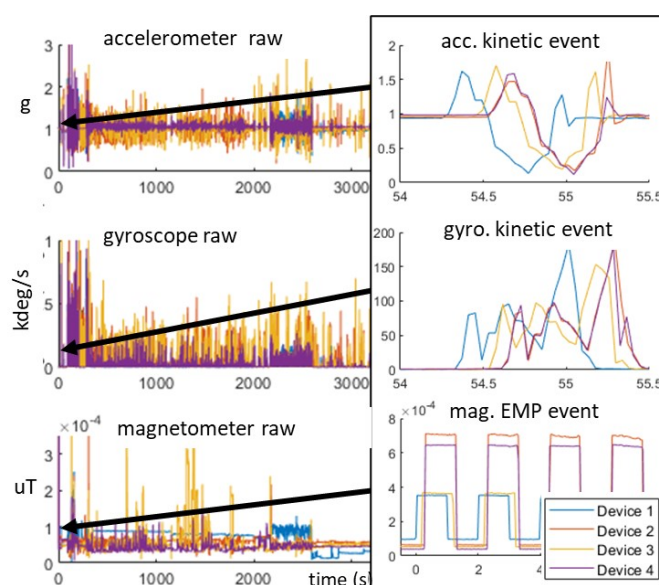


Figure 2. IMU magnitude data for 4 devices plotted against RTC time, highlighting "table slam" kinetic (accelerometer and gyroscope), and example of 4 equal-width EMP (magnetometer) pulses.

66 The rest of the paper is structured as follows: The preliminary proof-of-concept experiment and results
 67 are discussed (as originally presented in Gilbert et al. (2022)). We then introduce an extended method that
 68 improves synchronisation beyond the limitations of the sample frequency and describe an experimental
 69 setup to evaluate this. Finally we present the results of these experiments and discuss the wider practical
 70 implications of the work.

2 PRELIMINARY EMP STUDY

71 A simple electromagnetic pulse generator (EMPG) was built by attaching an electromagnet to an Arduino
 72 UNO via a full h-bridge, as shown in Figure 1. This EMPG was configured to transmit a 4 period length
 73 pulse at 0.5Hz. The electromagnet powered at 2W has a magnetic field strength of $0.2\mu\text{T}$ at 11cm. Below
 74 $0.2\mu\text{T}$ the magnetometer fails to measure the pulses giving an active range of 11cm.

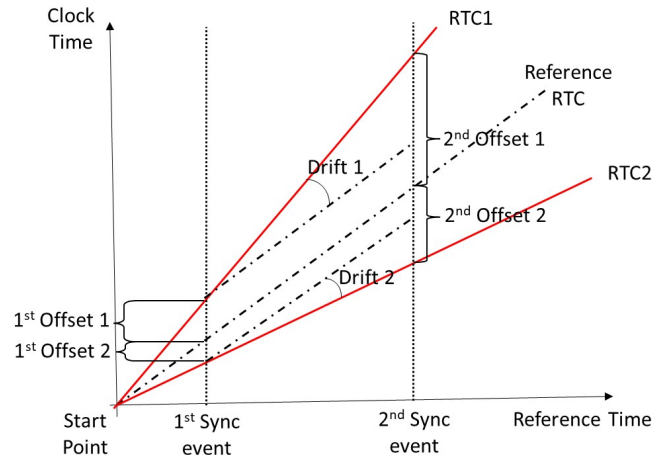


Figure 3. Timing diagram showing the offsets and drifts of 3 RTCs relative to one another.

75 Four MetaMotion R3 modules, from Mblet labs Inc, USA, were set up using an iPad. Each module
 76 was configured to logging mode. The magnetometer is activated to record at 25Hz. Because the kinetic
 77 events will be used as an approximation of the ‘gold standard’ (having been used in many previous works)
 78 against which the magnetic method will be evaluated, the accelerometer and gyroscopes are sampled
 79 at a higher rate of 100Hz. The gyroscope was set to $\pm 1600^\circ/s$. The accelerometer was set to $\pm 16g$.
 80 The magnetometer’s resolution is fixed at $\pm 1300\mu T$. The only physical requirement of the magnetometer
 81 method is that the sensors are within range of the EMPG. However, to ensure the efficacy of the kinetic
 82 method, the modules are placed in a holder so that they might be moved in synchrony together, as shown in
 83 Figure 1.

84 Two synchronising events were generated at the start and end of the recording. A 4 period-length
 85 electromagnetic pulse (EMP) event was generated using the EMPG. A kinetic event as described in Ward
 86 et al. (2018) was then completed by swiftly lifting and slamming the holder on a table. The devices were
 87 then worn by the experimenter for approximately 1 hour of arbitrary movement. Afterwards the devices
 88 were returned to the holder and the EMP and kinetic event repeated.

89 The raw 3-axis accelerometer, gyroscope, and magnetometer data of the devices were uploaded to an
 90 iPad and saved for processing in MATLAB. The orientation-invariant magnitude (Euclidean norm) of each
 91 sensor was calculated and mapped relative to epoch time. The timestamps for each device’s data are aligned
 92 at upload time to the iPad. This means that data points taken towards the end of the recording have the
 93 most accurate timing, with those towards the start of the recording subject to larger timing errors. The data
 94 for the 4 devices are plotted in Figure 2 with the first kinetic and EMP events magnified.

95 2.1 Preliminary Results

96 The data is aligned manually using the kinetic (accelerometer) events, this is done in a similar way to
 97 that described by Bannach et al. (2009). Specifically, the data is plotted and aligned manually until they
 98 appear most correlated according to the ‘expert opinion’ of the experimenter. To achieve this, an arbitrary
 99 device (device 1) is chosen as the reference to which all others are compared. The 1st kinetic event for
 100 each device is then aligned by translating their data. With the 1st events fixed, the data is then horizontally
 101 scaled (shortened or stretched) to align the 2nd events.

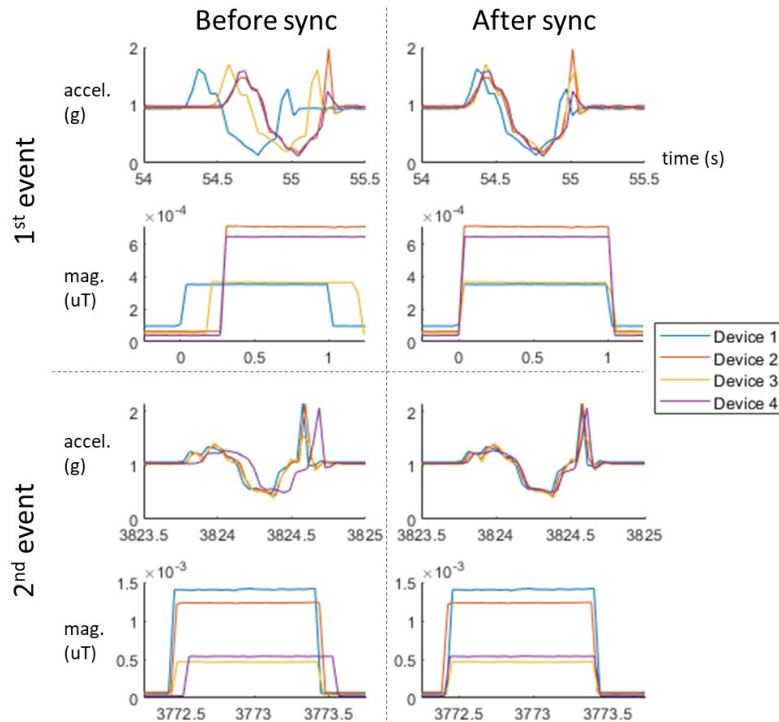


Figure 4. Closeups of 1st and 2nd kinetic (accel.) and EMP (mag.) events before and after synchronisation.

102 The RTC timing offsets for the two kinetic events (judged by expert opinion) are shown in Table 1. These
 103 show the offsets in ms of devices 2-4, relative to device 1. Note that after only 1 hour of recording, there is
 104 a large RTC offset of 267 ms between devices 1 and 2.

105 Table 1 also shows the relative clock drift, in parts-per-million (ppm), of each device's RTC. Drift is
 106 calculated using $10^6 * (D_d/D_1)$, where D_d is the difference in offsets between each event, and D_1 is the
 107 duration between the 1st and 2nd events for device 1. Refer to Figure 3 for a visual representation of the
 108 offsets and drift described in this paper.

109 The RTC crystal for each device has an accuracy of approximately ± 40 ppm, so as the epoch time
 110 moves away from the RTC synchronisation point the offset error will increase. The drift shown in Table 1
 111 between devices 1 and 2 of 67ppm indicates a large clock drift, but falling within the specified range
 112 ($< 40 + 40 = 80$ ppm for 2 devices).

113 To evaluate the EMP method, Devices 2-4 are re-aligned to device 1 by manually translating and scaling
 114 their data using the first rising edges of the 1st and 2nd EMP events. The difference between these EMP
 115 alignments and those of the kinetic events are shown in the rightmost columns of Table 1. A detailed plot
 116 of the events for the accelerometer and magnetometer before and after the EMP synchronisation process
 117 are shown in Figure 4.

118 2.1.1 EMP vs kinetic

119 Because there is no ideal ground truth for the timings, all results are calculated using distinguishable
 120 features in the data. One of the limitations on using kinetic events is that the signals have slight variations
 121 due to noise and micro-vibrations, thus making precise alignment challenging. This is one of the reasons
 122 that expert opinion is typically more accurate than automated correlational methods. Despite the fact that

(Vs. device 1)	Timings based on RTC			Timings based on EMP event	
	Drift (ppm)	1 st offset (ms)	2 nd offset (ms)	1 st offset (ms)	2 nd offset (ms)
Device 2	67.073	267	14	36	12
Device 3	39.502	168	19	34	10
Device 4	42.948	262	100	37	14

Table 1. Timing offsets between device 1 and the other IMU devices based on the RTC and EMP events for a 1 hour recording.

123 the devices in this experiment are fixed into a container and moved together, the variations in their kinetic
124 responses can still be clearly seen in Figure 4.

125 In contrast, the rising and falling edges of the EMP events are relatively consistent across devices. The
126 amplitude of the signals varies depending on the distance to the magnetic field generator, however this
127 is less critical for synchronisation purposes. The defined edges remove the ambiguity associated with
128 aligning a kinetic event. Because the shape and frequency of the EMP sequence are user-defined, it can be
129 configured to provide additional information, such as unique identifiers to differentiate separate experiments
130 or repeated sync events. In the rest of the paper, we make use of this flexibility to solve the problem of
131 sample-rate limited accuracy.

132 2.1.2 Limitations on synchronisation accuracy

133 After EMP synchronisation, the offsets measured by the kinetic event for devices 2 to 4 are
134 indistinguishable ($<3\text{ms}$). However, device 1 retains an offset of between 34 and 37ms compared to
135 the other devices during the first event (as visible in the top right kinetic plot of Figure 4 and shown in
136 the right 2 columns of Table 1). This post-synchronisation offset is a result of the limitation imposed by
137 the sampling rate. With a sample period s , a lower than s alignment error cannot be guaranteed using
138 only a single synchronisation edge. Given a sample frequency of 25Hz, a synchronisation error of up to
139 $1/25 = 40\text{ms}$ is possible. In the case of the MetaMotion R3 the magnetometer can be configured to sample
140 up to 300Hz giving a potential maximum error of approximately 3.3ms. However, such a high sample rate
141 is not always possible - nor desirable - for some applications when battery life and storage capacity is an
142 issue.

3 EXPANDED METHOD USING MULTIPLE PULSES

143 The accuracy of the fixed-pulse width method described above is fundamentally limited by the
144 magnetometer sample rate. The expanded method described below bypasses this limitation by using
145 a sequence of variable length pulses to locate a synchronisation event with sub-sample-rate accuracy.
146 Specifically, the method involves transmitting a fixed-width pulse w followed by a sequence of slightly
147 longer pulses until alignment is achieved.

148 The relationship between sample rate and capturing an EMP square wave can be formalised as follows.
149 If we say that m is the difference between an EMP edge and the next sample point, then m must be
150 $0 \leq m < s$ for a sample period of s . If the sample period decreases (rate increases), then the largest
151 difference between the EMP edge and sample point will also decrease.

152 If a square pulse has a width of w and a sample period s , then it is expected that the pulse will be sampled
153 $k = w/s$ times during its duration. Note that w should be a factor of s . However, if m is 0 an additional
154 sample point is taken on the falling edge, making the total number of sample points $k + 1$, this phenomenon
155 can be seen in Figure 5.

156 The expanded method uses this phenomenon to understand the alignment of the square EMP pulses to
157 the set of captured samples. This is done by transmitting an initial square pulse with width w and several
158 further pulses with a width of $w + a$, where a is the shift amount. This shift will result in the m value being
159 reduced by the shift amount, a , after the next pulse, as shown after Pulse 1 in Figure 6. The following
160 pulses will then have a distance $m - (p - 1)a$, where p is the pulse number, between the rising/falling edge
161 and the first sample. With each successive pulse, the distance between an EMP edge and the first sample
162 point will decrease. Eventually the distance will be small enough to allow an additional sample point. This
163 can be seen for the 3 samples, highlighted by dashed red lines, that fit within Pulse 3 in Figure 6.

164 It is possible to determine within a range the initial m value from knowing the chosen a and which pulse
165 has the additional sample point. For example if Pulse 1 has an additional sample point then $0 < m \leq a$,
166 as this increase of a allows enough time for the additional sample point to occur on the pulse. Every
167 subsequent pulse has an additional a shift from the initial pulse meaning $(p - 1)a < m \leq pa$ is true.
168 Therefore the shift amount, a , can be seen as a parameter which sets the maximum error. However reducing
169 a also increases the number of possible shifts required to guarantee an additional sample will capture a
170 pulse. The minimum number of pulses required to guarantee the additional sample is $s/a + 1$. For example
171 if the desired maximum error is 5ms and the sample period is 40ms, then the full synchronising signal will
172 need to be at least 9 pulses long ($40/5 + 1 = 9$).

173 The transient response of the electromagnet is also a crucial limiting factor. The solenoid used in this
174 experiment no longer had a stable transient response below a w of 300ms. Therefore considering that s
175 must be a factor of w and the default s for the module used is 40ms, it was decided to use a w of 320ms.
176 The length of the synchronising signal is then calculated by $s(w + a)/a + w$. With $w = 320$ ms, the 9 pulse
177 sequence signal will take 2.92s.

178 3.1 Additional encoding

179 Although not essential for the functioning of the method described, it can be useful for some applications
180 to encode further information into the EMP signal. For example, an identifying label might be added to
181 address any issues with large offsets between the portable-EMPG RTC and any IMU RTC, which could
182 lead to confusion and mis-identification of signals, see Figure 7.

183 Here we append a unique identifier number to the signal. This customisable label is appended after the
184 synchronisation signal, facilitating correspondence between the central records on the EMP and the signals
185 obtained from the IMUs. The trade-off, however, is an increase in signal length, resulting in an extended
186 time required to transmit the sequence of pulses. The signal length is dependent on the w value as well as
187 the desired identifier word length, n . The desired number of bits would be chosen considering the number
188 of synchronisation events required for an experiment. In addition to the identifying bits, one start and one
189 stop bit are added to the signal. The identifier length is approximately $w \times (n + 2)$. Therefore a 4-bit word
190 identifier with a w value of 320ms would last an additional 1.92s.

191 If the de-synchronisation of EMP is negligible compared to the time between synchronising events, the
192 removal of the identifier becomes a viable option, allowing for a reduction in synchronisation time without
193 compromising the synchronisation quality.

194 3.2 Experimental setup

195 The EMPG of Figure 1 was adapted to incorporate an RTC such that the EMP events could have a
196 centrally recorded reference timestamp. Additionally, the electromagnet was removed from the holder so

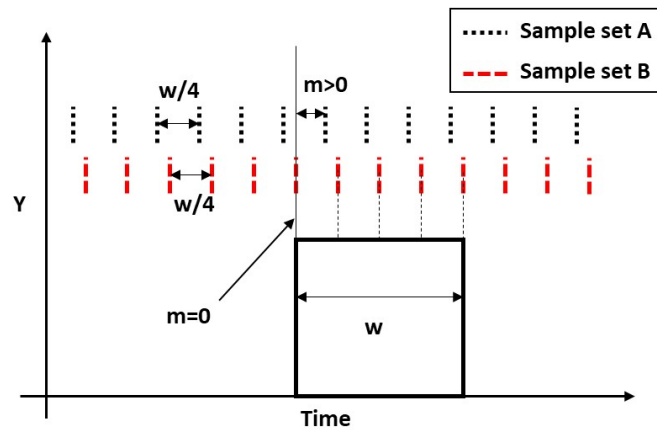


Figure 5. Example demonstrating how the alignment m dictates the number of samples capturing a pulse. Here the sample rate is $1/4$ pulse width, w . With $m > 0$ set A captures the pulse using 4 samples, while set B with $m = 0$ uses 5 samples.

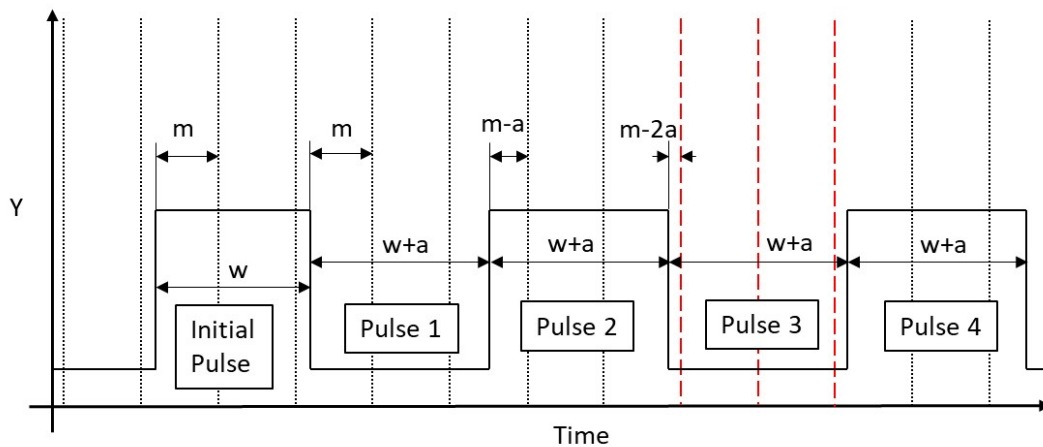


Figure 6. A graphical representation of the extended method demonstrating how the distance, m , between the starting edge of each pulse and the next sample reduces by the extended width, a . Note how pulses 1 and 2 only have two samples between the edges of the pulse, while pulse 3 has an additional sample point between its edges.

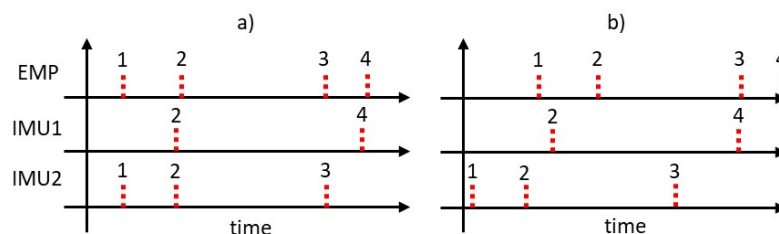


Figure 7. Example EMP events demonstrating typical and extreme de-synchronisation for two IMUs. a) Demonstrates how it is possible to associate the sync events from the portable-EMPG to the IMUs without a label using just their approximate location. b) Demonstrates how a greater offset between the RTCs of the portable-EMPG and the IMUs requires a label to determine which events belong together: for both IMU1 and IMU2 the 2^{nd} event could be mistaken for the 1^{st} if the labels were not present.

197 that it could be brought to individual IMUs. This new portable-EMPG uses a low-power electromagnet that
198 could be directly powered by an Arduino MKR 1010 board (provided by SeeedStudios¹). The experiment
199 is conducted on a level surface, specifically a flat table, for two sessions of two hours each using multiple
200 IMUs (MetaMotionRs) whose data is recorded through the MetaBase app. 8 IMU devices were set up to
201 record accelerometer and magnetometer data at a sample rate of 25Hz. Meanwhile, a 60FPS video was
202 recorded, showing a laptop displaying the Unix timestamp using the website (time.is/Unix_time) while
203 the events occurred. This recording allowed a timestamp to be taken of the synchronisation events. This
204 timestamp was then used to locate the events on MATLAB during post-processing.

205 The first event begins with generating an EM pulse using the portable-EMPG for each of the 8 IMUs.
206 Following this, the IMUs are placed into a 3D-printed container, designed to reduce the independent motion
207 of the devices. Once all are placed in the container, the container is quickly lifted and hit back onto the
208 table, creating a kinetic event. Following two hours of recording arbitrary accelerometer and magnetometer
209 data of the devices on the table, the IMU devices were removed from the container and the EMP event
210 was repeated for each of the IMUs individually, while the IMUs were placed on the table with their Z axis
211 facing up. Following this, the IMUs were placed back into the container and a second kinetic event was
212 performed. The orientation-invariant magnitude (Euclidean norm) was calculated for all data.

213 3.3 Procedure

214 We conducted two separate 2-hour experiments to evaluate the method. One was conducted with an a
215 value of 5ms, while the other involved a combination of 10ms and 20ms. These parameters were chosen
216 based on successive halving of the sample period (40ms). The 2nd experiment, using 10 ms and 20 ms,
217 demonstrates that rapid less accurate synchronisations as well as slower more accurate synchronisations can
218 be performed within a single session. Each of the IMUs were synchronised using the methods previously
219 described: using RTC timestamps only, using the original EMP method from the preliminary study, using
220 the expanded EMP method described in this paper, and using cross-correlation of kinetic events. The cross-
221 correlation of kinetic events was calculated by windowing the kinetic event, interpolating the timestamps
222 and using the `xcorr()` method on MATLAB to determine the lag that results in the greatest correlation
223 between the different IMUs; the IMUs time series were then translated by this lag value. All offsets are
224 calculated with respect to the expert opinion based on the kinetic events.

225 3.4 Results

226 Figure 8 shows an example of the expanded EMP event sequence from one of the IMUs in this experiment.
227 Note how the 3rd pulse has 9 sample points while the other pulses only have 8. This indicates that the EMP
228 event is offset by up to 15ms ($3 \times 5\text{ms}$) and must be adjusted accordingly.

229 The signal offsets for each IMU are presented in Table 2 (for $a = 5\text{ms}$) and Table 3 (for $a = 10$ and 20ms)
230 for the 4 synchronisation scenarios. The plots in Figure 9 also show the kinetic events of all IMUs across
231 the four scenarios at $a = 5\text{ms}$.

232 As found in the preliminary study, the RTC-only synchronisation performs worse of all, with offset errors
233 between 3 ms (Device 1) and up to 336 ms (Device 7). The original EMP method improves this by capping
234 errors within the 40 ms sample period, with the largest error being 36 ms (Device 2).

235 Across all devices and a settings, the expanded method produces results most closely aligned with expert
236 opinion. Table 2 reveals absolute offsets across the recording of no more than 7 ms for the expanded EMP

¹ SeeedStudios Grove Electromagnet: <https://wiki.seeedstudio.com/Grove-Electromagnet/>

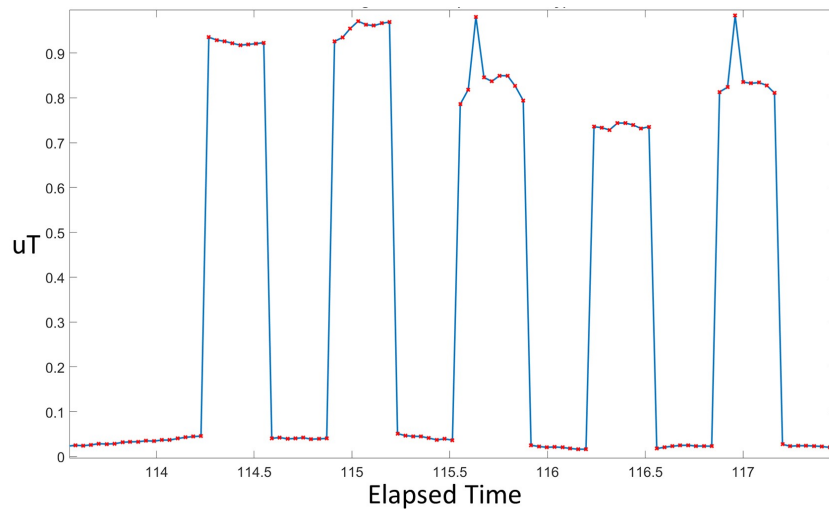


Figure 8. Electromagnetic pulses sampled by an IMU with the pulse width set to give a maximum error of $a = 5$ ms. Note that the 9-sample situation occurs during the 3rd pulse.

IMU No.	$a = 5$ ms							
	1	2	3	4	5	6	7	8
RTC sync	3	64	-95	-150	108	-56	-336	30
Original EMP	3	-36	15	12	-14	-21	-4	-23
Expanded EMP	6	-4	3	-7	-1	-5	-4	0
KE+CC	3	23	-24	-23	28	-15	-13	30

Table 2. Offsets (in ms) vs expert opinion for 4 methods: RTC synchronisation, original EMP method, expanded EMP method with $a = 5$ ms, and kinetic event + cross-correlation method.

237 method (Device 4), as comparable to offsets of up to 36 ms for the original EMP (Device 2). Similarly,
 238 for the 2nd experiment with $a = 10$ in Table 3, the maximum recorded offset is 10 ms (Device 3), and for
 239 $a = 20$, the maximum is 18 ms (Device 7). These values align closely with what might be expected from
 240 the desired a settings.

241 Although most of the results for the expanded method fall within the specified a value, for 2 devices the
 242 offset rises above this (Devices 1 and 4 in Table 2). This is explained by the additional transient response
 243 time of the electromagnet, which can be up to 3 ms. So whereas in an ideal system the offset error would
 244 be capped at a , in a real system this would actually be $(a + 3)$ ms.

245 Notably, the kinetic cross-correlation method achieves a very high variability in error - from between 3
 246 ms (Device 1, Table 2) to as much as 142 ms (Device 7, Table 3). This can best be explained by the reliance
 247 of this method on calculating correlations across accelerometer signals that are noisy. Although plot (c)
 248 in Figure 9 achieved the highest between device correlation scores, it is clearly not as well aligned as the
 249 expert-based alignment of plot (e) - or indeed the expanded EMP method shown in plot (d).

4 DISCUSSION

250 The main goal of this paper is to demonstrate an in-situ synchronisation method which is able to achieve
 251 sub sample accuracy without requiring any modifications to the hardware or firmware of commercial IMUs.

IMU No.	$a = 10$ ms				$a = 20$ ms			
	1	2	3	4	5	6	7	8
RTC sync	-26	114	-68	-143	117	-22	-322	6
Original EMP	16	-26	3	-8	-11	26	0	-9
Expanded EMP	6	0	10	0	-10	10	18	-5
KE+CC	-26	7	-67	-58	117	102	142	87

Table 3. Offsets (in ms) vs expert opinion for 4 methods: RTC synchronisation, original EMP method, expanded EMP method with $a = 10$ ms (IMU1-4) and $a = 20$ ms (IMU5-8), kinetic event + cross-correlation.

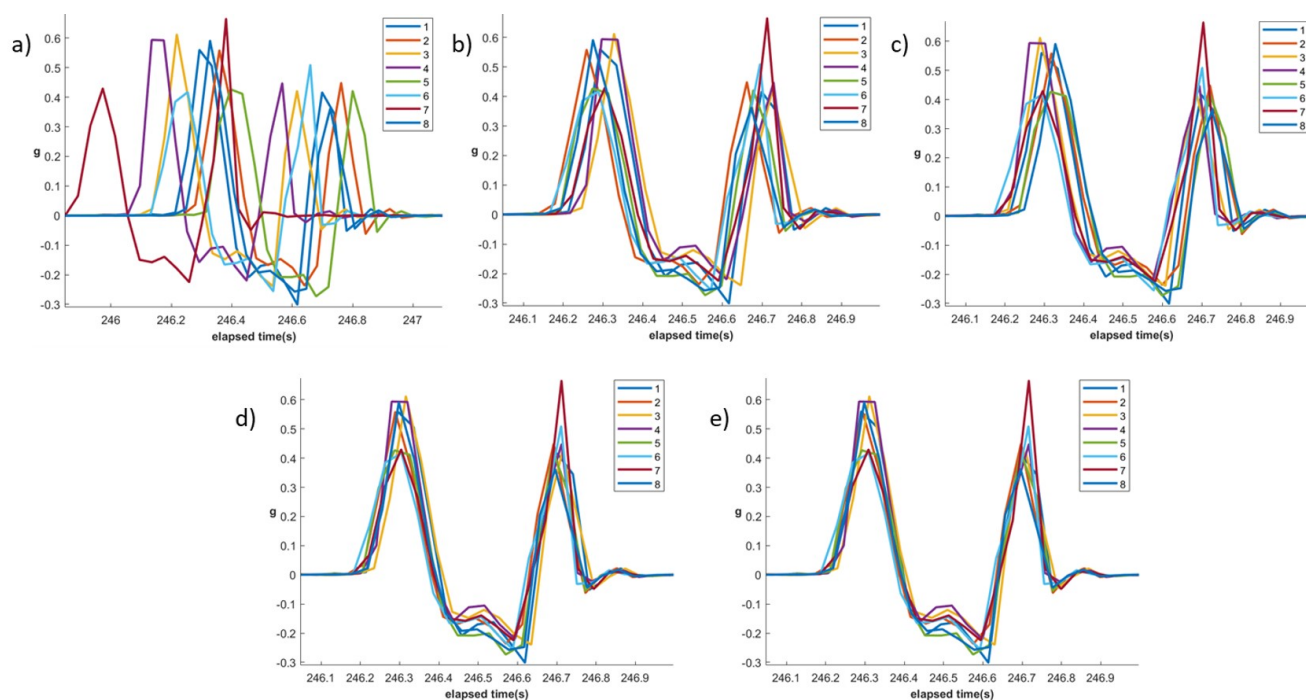


Figure 9. The 1st kinetic event signals of 9 devices after a) RTC sync b) standard EMP sync c) kinetic event + cross corr d) expanded EMP sync e) expert opinion. Note that the output obtained using the expanded method is most similar to the expert opinion.

252 A simple method of using electromagnetic pulses was first demonstrated that achieves an accuracy
 253 dependent on the sample frequency. An expanded method then demonstrated how sub-sample accuracy can
 254 be achieved using encoded pulses and a central RTC.

255 Unlike in similar methods, the method demonstrated here does not heavily rely on the amplitude of the
 256 recorded event. The method only requires that the edges of the synchronising signal are distinguishable.
 257 The distances between the IMU devices and the synchronising unit do not need to be fixed, instead the
 258 IMU device must only be within the active range of the portable-EMPG. This means IMU devices are
 259 not required to be removed from their experimental setup to be synchronised, which is particularly useful
 260 when deploying a large number of IMU devices in wearables. Similar methods require the devices to be
 261 removed from the participants and placed into a synchronisation box, which when working with a large
 262 number of IMUs can be a long process prone to mislabelling. Additionally, the size of the synchronisation
 263 box limits the number of IMUs that can be used in the experiment as similar methods require all the
 264 devices to be synchronised simultaneously. The method demonstrated by this paper does not require a
 265 synchronisation box nor simultaneous synchronisation meaning there is no limit to the number of IMUs
 266 that be synchronised.

267 Two configurations of the expanded multi-pulse method were demonstrated, with the maximum error
268 parameters set as $a = 5\text{ms}$ and a combination of $a = 10\text{ms}$ and $a = 20\text{ms}$. Note all three accuracy values
269 are sub-sample accuracy, which for a 25Hz magnetometer is 40ms. The first configuration shows how
270 the method can be used to achieve low synchronisation offset comparable to similar studies, while the
271 second configuration shows how the user could choose to go with quicker synchronisation events when low
272 offsets are not required. Additionally, the second configuration also shows how multiple offset values can
273 be used in a single session, giving the user of the method even more flexibility, allowing them to choose an
274 appropriate offset on the fly in response to live events.

275 4.1 Limitations

276 Although the expanded method synchronises IMUs using the edges rather than the amplitude of the
277 received signals, it still needs to be guaranteed that the signal can be distinguished from the noise
278 background. Currently, the system is limited by the Electromagnetic Field (EMF) Regulations from
279 applying powerful electromagnets ICNIRP (2009). This constrains the maximum effective distance for
280 synchronisation between EMPG and IMUs. The current active range of 11cm limits the number of
281 applications this method will be effective in, requiring small synchronisation points. One caveat to this
282 limitation is that the portability of the proposed method, and the fact that a central reference RTC is used,
283 means that these synchronisation points can simply be brought close to wherever each IMU is located if
284 the experiment permits it.

285 A further limitation of this method is that the synchronisation of all devices is dependent on the central
286 RTC of the EMPG. This RTC is also susceptible to drift. Figure 3 is a timing diagram showing the offsets
287 and drifts associated with the inaccuracies of an RTC. This diagram shows how two IMUs with opposing
288 offsets and drifts can result in large de-synchronisation of clocks. Note that in this diagram the drift of the
289 electromagnetic generator's RTC is less than the two IMUs, in practice this may not be the case as this
290 method is focused on synchronising the clocks of multiple IMUs rather than determining absolute timing.

291 In situations where the portable-EMPG's RTC could induce significant desynchronisation, then an
292 additional 6-bit identifier can be appended to the signal to help differentiate sync events. The downside to
293 this is that it would result in an extended synchronisation time (1.92s in the example given in this paper).

294 Overall, the expanded method can achieve higher synchronisation performance by increasing the signal
295 length; however, degree of accuracy is constrained by the transient response of the electromagnet. In
296 experiments, the transient response resulted in an approximate width of 3 ms for each edge, which is a
297 factor that should be taken into consideration when employing this approach.

5 CONCLUSION

298 This paper introduces a new method for synchronizing wearable IMUs using a portable electromagnetic
299 pulse generator (portable-EMPG) to transmit magnetic pulses. This approach potentially enables
300 synchronisation of multiple wearable IMUs without requiring their removal from users. Through
301 experiments with different maximum degrees of error (5ms, 10ms, and 20ms), we demonstrate the
302 method's flexibility in adjusting synchronisation accuracy to user requirements. The trade-off is that more
303 precise synchronisation requires a longer sequence of EMP events. Additionally, we introduce the idea of
304 using further encoding on the electromagnetic pulse to act as an identifier, allowing the user to identify
305 specific events with a binary word.

306 Our study identifies a 3ms error related to the solenoid's transient response and acknowledges drift and
307 offset errors associated with synchronizing to a central RTC. Future research will focus on extending
308 the portable-EMPG's active range and improving timestamp accuracy through Wi-Fi integration. These
309 advancements aim to enhance the reliability and effectiveness of the synchronisation technique, making it
310 applicable across various domains reliant on precise IMU data synchronisation. This work contributes to
311 the development of synchronisation methodologies in inertial measurement systems, promising improved
312 data accuracy and usability in practical applications.

AUTHOR CONTRIBUTIONS

313 TG and ZL are joint first authors of this work. TG conducted the initial study, and ZL developed and
314 evaluated the follow-on work. TG, ZL, and JW contributed equally to the development of the concept,
315 interpretation of the results and presentation of the manuscript. SD and AH provided additional intellectual
316 contributions towards the concept and final manuscript.

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DATA AVAILABILITY STATEMENT

318 The datasets and and Matlab code for this study are available here: [github.com/jThumus/Electromagnetic-](https://github.com/jThumus/Electromagnetic-synchronisation-of-multiple-IMUs)
319 [synchronisation-of-multiple-IMUs](https://github.com/jThumus/Electromagnetic-synchronisation-of-multiple-IMUs).

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