MULTI-SENSOR POSITIONING SYSTEM DESIGN EXERCISE

Contents

Exercise Format

In Requirements of the Application, the context and design requirements are described without referring to a specific technology. Followed by Technology Characteristics: where technologies are introduced, methods of positioning, their outputs and errors. Next, in Integration, a proposal of how the outputs can be integrated into a resilient system. Finally, Design Justification highlights the chosen sensors characteristics and suitability to the application compared to other technologies.

Requirements of the Application

Context

The consumer application is designed for guided tours in museums and galleries. A nation's government is the target consumer. The primary aim is to remotely track visitor locations in real-time and display them on a floor map in the control room. Another key aim is to relay audio and text information relevant to exhibitions in the zone of the user's location. The secondary objective is to provide users with social distancing proximity alerts. Current Coronavirus (COVID-19) social distancing guidelines require two metres between members of different households and a one-metre distance if there are relevant precautions: a well-ventilated building in addition to face coverings being worn (UK Government, 2021). The application is designed to alert when customers from different households breach a two-metre buffer. The two primary objectives are categorised as logistical and administrative. The secondary objective is optional, classed under health and security.

Performance

The application requires a remote, real-time, continuous positioning solution. There should be low system latency < 1 second. A constant solution is a priority. Therefore, solution continuity is crucial; a regular update rate is necessary, at least 1 Hz (1 cycle/second). Context-awareness is required to detect changes in motion: stationary, walking ~ 5 km/h and running ~ 20 km/h. Further information on requirements related to context is in Table 1. Individual accuracy for the data outputs are not stated, as the overall system accuracy at an aggregated level is the main priority.

Table 1 ***Application requirements necessary for the museum or gallery indoor tracking system.***

Objective	Data Output	Systems Horizontal Accuracy (X) (position errors)	Systems Vertical Accuracy (Y) (position errors)	Coverage	Update Rate	Availability
Tracks user's location and display on a floor map (Primary)	XY Velocity Acceleration Attitude Angular rate	0.5m (95%)	Building floor detection	~20m	>1Hz	> 99%
Tracks user's location in relation to the Zone (Primary)		3.0m (95%)		~5m	>1Hz or when triggered	> 99% or > 99.9 when triggered by the user
Social distancing alert (Secondary)		0.5m (95%)			>1 Hz	> 99%

Environmental Constraints

The application is required to work on land and indoors, a closed environment. Museums and galleries operate at an average humidity of 45% and a temperature between 18-20°C. Signal attenuation is created by non-line of sight (NLOS), multipath, blocking from surfaces and continuously moving people. The design needs to produce correct outputs operating in those conditions.

Economic Constraints

Table 2 displays the annual budget in dollars for museums in North America. High range large to global museums and galleries are the target consumers. A museum or gallery spending 5% of its annual budget on technology and innovation creates a feasible $2.5M-$12.5M budget, approximately £1.8M-10.7M; this includes the purchasing of hardware and software, installation and subscription-based maintenance.

Table 2 ***Annual museum budget sizes North America****. Source: Data were taken from (Bensahih , 2020)*

Annual Budget	Small Museums	Medium Museums	Large Museums	Global Museums
Low Range	< $100K	$500K-$3M	$15M-$50M	$100-$250M
High Range	$100K-550K	$3-$15M	$50M-$100M	$250-More

Estimated quartiles of daily museum and gallery visitors (2018/2019) are presented in Table 3. The British Museum, an example of a global museum, had the highest visitor count. Each visitor has to wear a device in order to be tracked. Estimations, based on Table 3, indicate 2000-5000 units would suffice most customers. The target consumer is the Department for Digital, Culture, Media & Sport (DCMS) and international equivalents.

Table 3 ***Daily museum and gallery visits 2018/2019****. Source: (Department for Digital, Culture, Media & Sport, 2021)*

Minimum daily visits	16
Daily visits first quartile (25th percentile)	852
Median daily visits (50th percentile)	2171
Third quartile (75th percentile)	8800
Maximum daily visits	16737
Mean daily visits	5236

Engineering Constraints

Visitors range from children to adults. The consumer application needs to be handheld (portable) and made from a durable material. Figure 1 illustrates a prototype design for the user equipment and Table 4 summarises the design requirements.

Table 4 ***Requirements of the visitors' user equipment***

Dimensions	158 mm x 77.8 mm x 8.1 mm
Weight	~300 g
Screen size	6.1-inches
Power consumption	12 hours of battery life
Software Application requirements	• Display alert messages from a central server • Display text and audio relevant information based on server communication
Hardware requirements	• 3 buttons up/down/select • Audio jack • USB-C (charging /updates) • Wi-Fi connectivity • The sensors described in Technology Characteristics

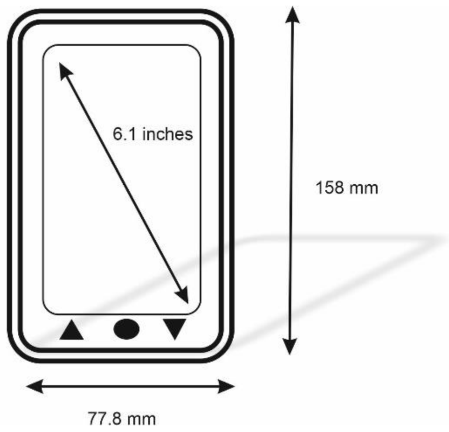


Figure 1 ***Visitor user equipment***

Technology Characteristics

The section presents three sensor technologies and one navigation procedure for the application design. Near Field Communication (NFC), Ultra-wideband (UWB) and Inertial Navigation System (INS) are the three positioning technologies. Map Matching is the procedure.

Map Matching

The museum or gallery map acts as a defined local coordinate reference system; therefore, the position solution is relative compared to an absolute coordinate position (global reference). Floor plans that make-up the building are used in map matching to display the application's output at the central server. The server will have a man-machine graphical interface to visually monitor customers, depicted in Figure 2. Spatial coordinates produced by a position solution references a zone on the database, then offers the user relevant text and audio information relevant to the zone. Additionally, real-time updates of visitor positions and individual buffers can monitor social distancing and track potential viral spread; each device is registered to a visitor.

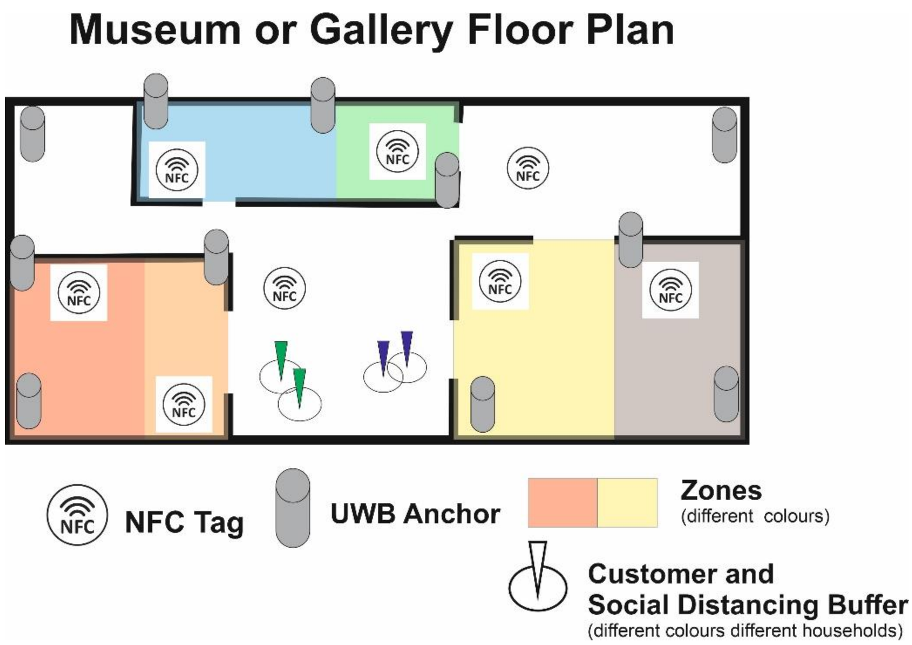


Figure 2 ***An example floor plan, an output of map matching***

Ultra-wideband

Ultra-wideband (UWB) is part of the radio frequency (RF) spectrum. UWB transmits 3.1-10.6 GHz operating at a bandwidth ratio to carrier frequency > 20%. UWB has an accuracy of between 10-30cm. It is infrastructure dependent. Built-up of tags (at unknown locations), these send out RF transmissions, called polls and anchors that record timestamp and return signals. Anchors, at a known location, require connection to the internet via either Wi-Fi or Ethernet, sending position solutions to a network/server for map matching and position solution.

Time of Flight

Figure 3 presents a real-time UWB positioning solution using Time of Flight (TOF), used by standard industry UWB devices. The two-way ranging technique uses trilateration (3) or multilateration (>3) by calculating the Euclidean distance between tags and anchors. A minimum of three anchors is needed for a 2D solution (x y) and four for 3D (x,y,z). RF waves are sub-nanosecond pulses travelling at the speed of light c. The user equipment will contain a tag that sends out a poll, T_{sp} (Time start poll). Anchors receive the poll recording the time T_{rp}, then sends a timestamp signal response to the tag T_{sr}. T_{rr} is the time the tag receives the response. The final signal T_{sf} is sent from the tag to the anchor recording the T_{rf} (Time receive final). Distance can then be calculated by multiplying TOF by the speed of light (Nanjing Woxu Wireless Co.,Ltd, 2018). Distances form ranging circles, with anchors in the centre, where the radii intersect is the tag/user's location (see Figure 3).

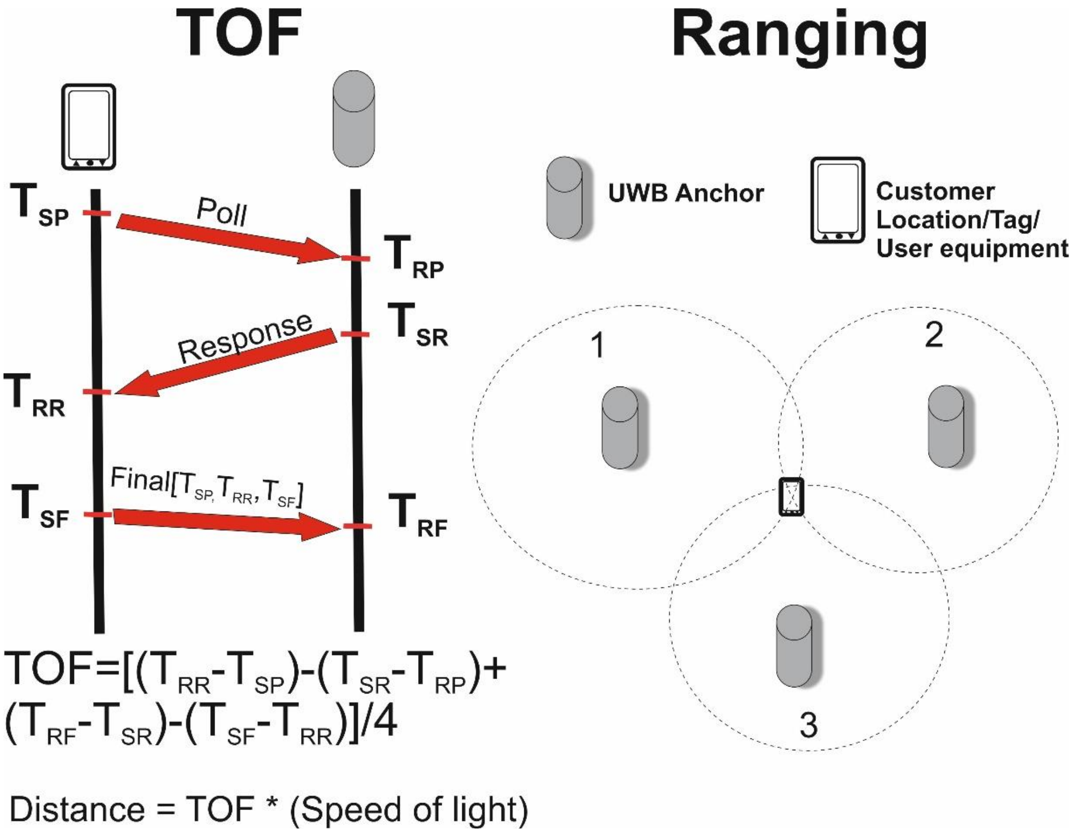


Figure 3 ***TOF formula, two way ranging and diagram*** *Source: Data modified from (Groves, 2013) (Nanjing Woxu Wireless Co.,Ltd, 2018)*

Equation (2) is the three-dimensional transformation of Equation (1) which both form part of the UWB localisation algorithm presented by Liu et al., in a 2019 experiment that investigated UWB accuracy for indoor positioning.

$$t_i = \tau_i + t_0 = d_i /c + t_0 = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2}/c + t_0 \quad \textbf{(1)}$$

$$d_i = \sqrt{(x_i + x)^2 + (y_i + y)^2 (z_i + z)^2}\ (i = 1,2, \ldots, n) \quad \textbf{(2)}$$

t_0	time radio signal is transmitted by tag
t_i	time anchor receives radio wave from tag
τ_i	radio wave tag to anchor propagation time
d_i	anchor to tag distance
x_i, y_i, z_i	anchor coordinates
x, y, z	tag coordinates

For a solution, a minimum of three observations (anchors) are needed. However, it will lead to redundant observations in the calculation. Least squares adjustment can be applied to the tag coordinate equation to minimise redundancy. The technique statistically finds the most likely coordinates. In the 2019 experiment, a Tukey weight factor was introduced to remove measurements with significant residual errors. The output of the TOA is spatial coordinates in a localised system.

Error Sources

UWB error sources include:

- clock drift between anchors and user equipment due to unsynchronised clocks recording transmissions, calculating and over or underestimated ranges;
- radio frequency noise and thermal noise interrupting the reported signal;
- multipath leading to incorrect peaks identified as direct path signal resulting in incorrect pseudo-ranges being calculated;
- NLOS, model violation and attenuation.

Inertial Navigation System

The Inertial Navigation (INS) is a self-contained system that contains an inertial measurement unit (IMU) sensor which takes measurements to detect motion changes.
A 9-axis IMU estimates position, orientation and velocity using:

- 3-axis gyroscope, angular rate sensor (deg/s), X, Y, Z;
- 3-axis accelerometer, acceleration (g), X, Y, Z; and
- 3-axis magnetometer, flux (G), X, Y, Z.

Pedestrian Dead Reckoning

Pedestrian Dead Reckoning (PDR) is a method that uses the INS outputs to calculate a user's position based on a previously known location. The method proposed for the application outputs the heading (attitude), step length and an updated position: a starting known position is needed for initialisation. A complementary sensor will be used (UWB or NFC).

PDR Localisation

The 9-axis IMU detects the heading, roll, and pitch of the user's motion, based on the sensor's axis frame. It is detecting whether they are stationary or moving. Outputs are then fused using the Madgwick algorithm in Equation (3) (Madgwick, et al., 2011). The results are sent to the network and combined with the map matching process to provide a heading solution.

$$\begin{cases} {}^S_E q_{est,t} = \alpha_1 {}^S_E q_{\omega,t} + \alpha_2 {}^S_E q_{\nabla,t} \\ \alpha_1 + \alpha_2 = 1, 0 \le \alpha_1 \le 1, 0 \le \alpha_2 \le 1 \end{cases} \quad \textbf{(3)}$$

${}^S_E q_{\omega,t}$	Attitude (gyroscope)
t	Time
${}^S_E q_{\nabla,t}$	Attitude (magnetometer and accelerometer)
α_1, α_2	Weighting coefficients

Heading

A significant source of error in PDR is the deviation from the true position due to the accumulation of errors over time from an incorrect step length, velocity and heading caused by noise. An approach to reduce the error in heading is to combine a wind direction map and the building map thus increasing system resilience (Liu, et al., 2019). The floor map (Figure 2) of a museum or gallery is divided into 16 heading directions with intervals of 22.5° (Figure 4). The INS heading angle output is matched to the wind direction interval. The interval is then adopted as the users heading.

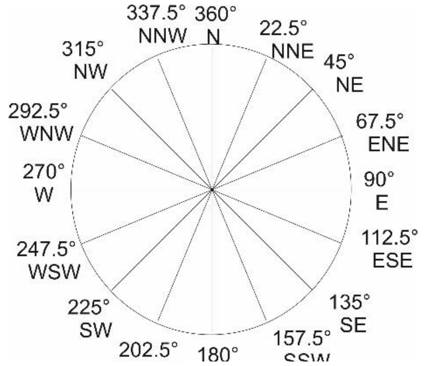


Figure 4 ***A wind direction map with 16 headings***

Step Length and Step Detection

Visitors range from children to adults; hence step length and gait vary. Both are integral to an accurate PDR solution. Acceleration changes detected by the INS are used to detect gait. The design presents a model for the step length algorithm proposed by Weinberg (2002). Equation (4) calculates the user's step using the root mean square of the accelerometer values. Equation (6) estimates the users step length, likewise using acceleration values, the maximum and minimum. ꞃ is a coefficient determined by a ratio between the actual and estimated reference path: Equation (5). Equation (7) final output, $P_{u,k}$ is a spatial coordinate.

$$a(t) = \sqrt{a_x^2(t) + a_y^2(t) + a_z^2(t) - g} \quad (4)$$

(t)	Time
$a(t)$	Synthetic acceleration
g	Acceleration of gravity (9.8 m/s 2)
$x\ y\ z$	Acceleration values

$$\eta = d_{real}/d_{estimated} \quad (5)$$

$$S = \eta \cdot \sqrt[4]{\alpha_{max}(t) - \alpha_{min}(t), t_{k-1}^{s} < t \leq t_k^s} \quad (6)$$

t_k^s	Detected step time
α_{max}	Maximum acceleration
α_{min}	Minimum acceleration
t	Time
η	Coefficient, Equation (5)
S	Step length

$$P_{u,k} = \begin{bmatrix} E_k \\ N_k \end{bmatrix} = \begin{bmatrix} E_{k-1} + S_k \cdot \sin\theta_k \\ N_{k-1} + S_k \cdot \cos\theta_k \end{bmatrix} \quad (7)$$

$P_{u,k}$	Current device position
S_k	Current step length (estimated)
θ_k	Heading orientation (estimated)
E_k	North coordinate
N_k	East coordinate

INS Errors

INS errors include:

- cross-coupling, which can be solved through sensor calibration;
- random noise/random walks vibration-induced, electrical noise and high-frequency noise that can be mitigated by using lowpass filtering;
- scale factor, caused by axis misalignment;
- magnetic measurement errors, created by environmental anomalies and incorrect calibration; and
- the PDR algorithm presented does not mention whether only forward steps are calculated in step detection; side steps and walking backwards could create incorrect readings (Groves, 2013).

Near Field Communication

Near Field Communication (NFC) is a bidirectional wireless radio wave technology. It has a 13.56 MHz signal and a bandwidth <424 Kbit/s.There are three primary operations; 1) peer-peer, 2) reader/writer and 3) card emulation (Ozdenizci, et al., 2015). The design uses the reader operation, as presented in Figure 5.

A battery-powered NFC device creates its own RF layer; it is an active device. Tags are passive because they can not generate an RF layer. When an active NFC enabled device, comes into contact with or within 10cm of a tag's antennae; the produced RF signal starts the tag, loading an algorithm. It then transfers the stored coordinates in an NFC Data Exchange Format (NDEF). The user's equipment onboard system match the coordinates to the zone. Then retrieves and displays information relevant to exhibits in the zone.

Simultaneously the coordinate data is sent to the network over WI-Fi to aid in the positioning solution. It is a real-time positioning technology but relies on user initiation, making it an instantaneous, not continuous solution.

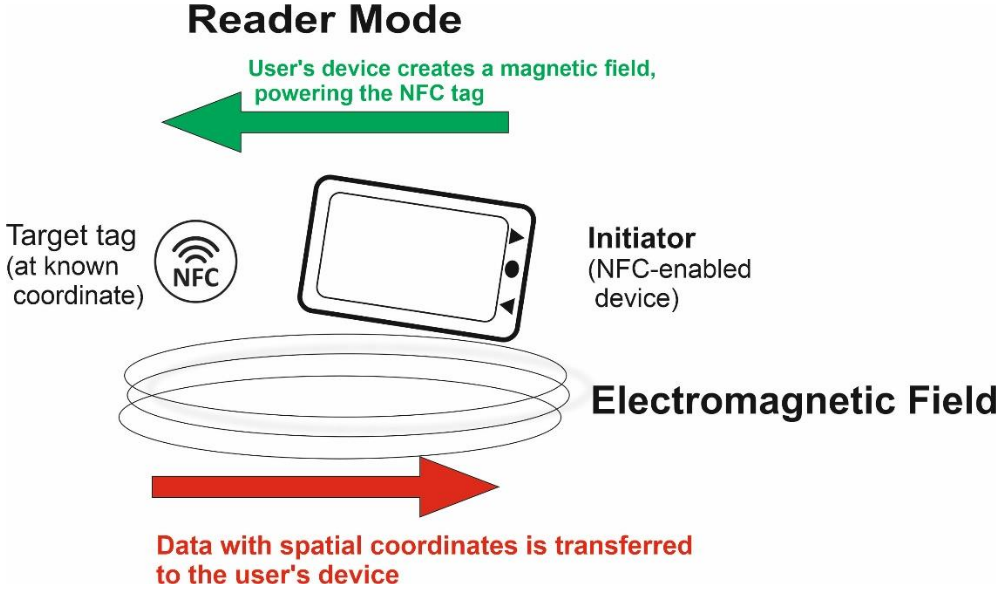


Figure 5 ***Data transfer between an initiator and a tag***

Error Source

NFC is an infrastructure dependent system, similar to UWB. Errors can form from:

- human error, loading the wrong coordinates; and
- an out of date database.

Regulation and Standards

The application is an electromagnetic device which must be regulated and adhere to standards. UWB used in the device would fall under the IEEE (Institute of Electrical and Electronics Engineers) organisational standards and part of the IEEE 802 LAN/MAN Standards Committee. The committee covers Local Area Network (LAN) standards and Metropolitan Area Network (MAN) standards and defines waveforms and modulations (Siwiak and McKeown, 2004). The NFC chip used will need to be in line with ISO/IEC 14443 and FeliCa regulations for RF layer communication.

Integration

Figure 6 shows how the outputs of the technologies are fed into algorithms to form a loosely coupled integrated system. The NFC, when triggered, acts as a primary calibration for the system; it should be given a greater weighting in the solution than UWB and PDR. Wi-Fi requested in the Engineering Constraints (Table 4) provides continuous communication between the user equipment and network and most importantly, to synchronise the UWB and PDR systems. The two systems update at a different rate so an onboard or network solution is necessary to unify them. The output of the system is spatial coordinates, referenced from the floor map.

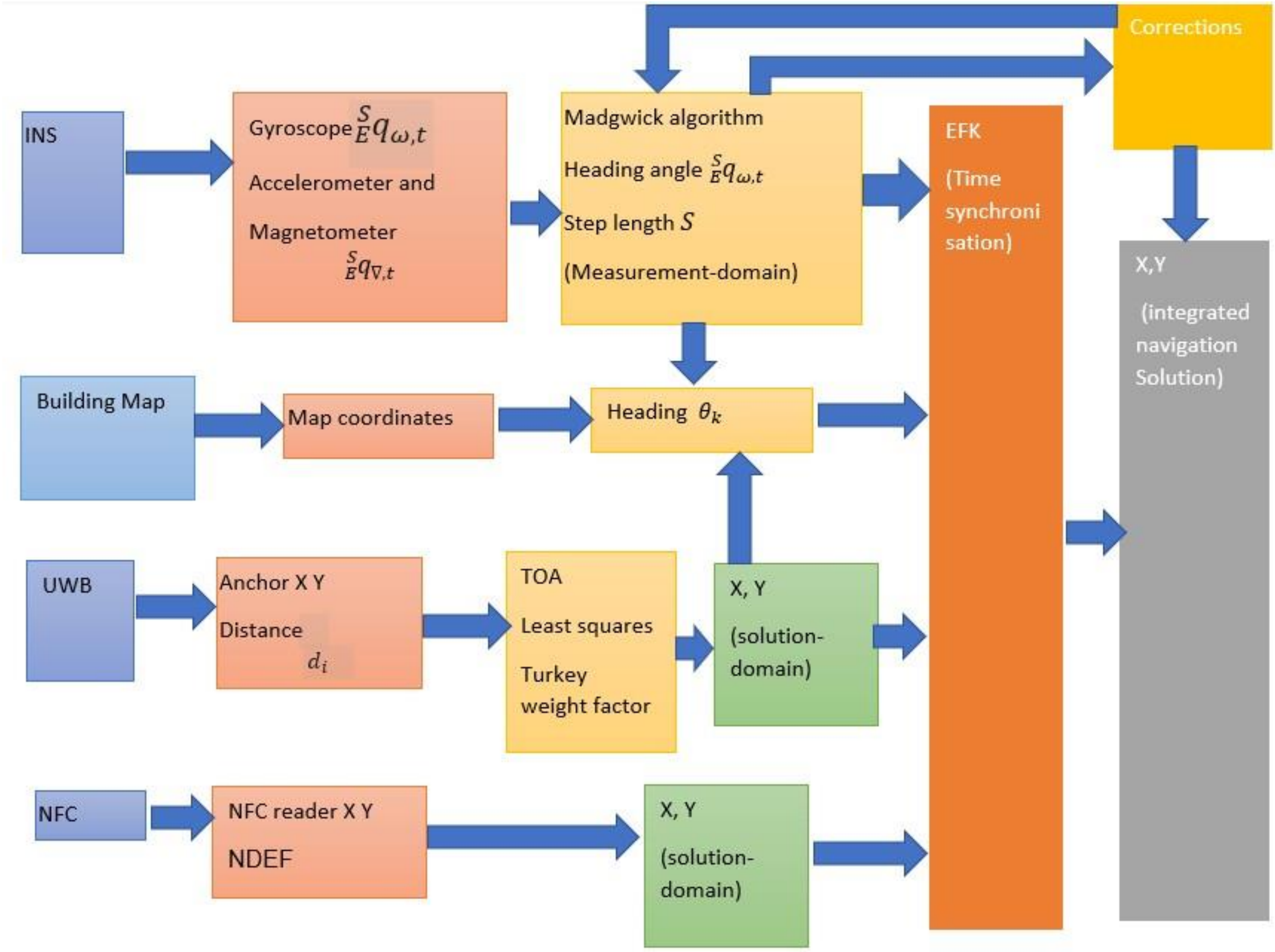


Figure 6 ***A Loosely coupled UWB/INS/PDR/Floor map integration***

Extended Kalman Filter (EKF)

Data outputted by the UWB and INS have uncertainties in velocity, acceleration, heading and position. Aside from human error, the likelihood of NFC being incorrect is highly unlikely. The Kalman Filter (KF) based on Bayesian filtering, assumes Gaussian distribution. KF is an estimation algorithm using past measurements that contain inaccuracies due to continuous noise and signal interruption. The iterative process uses linear quadratic estimations (LQE) to estimate true position. The fundamental limitation of KF is that it assumes the system is linear, which it is not. The Extended Kalman Filter (EKF) assumes the system is non-linear. Therefore, EKF is suggested to integrate the floor map, PDR, UWB and NFC.

Resilience and Application Requirements

Integration of complementary sensors with EFK overcomes some of the errors and drawbacks when using one technology. PDR is continuous and can provide solutions when NFC is not triggered, or the UWB signal is weak or not available. Leading to improved continuity and robustness of the system: a solution is provided when one fails. Likewise, the multi-epoch integration system feeds back corrections to the INS system; UWB and NFC provide the correct positions to calibrate the PDR. In the loosely coupled integration system, the UWB and NFC maintain standalone measurements as backups. Further adding another layer of robustness and resilience, there are sufficient sensors to operate when subsystems fail.

The adaptive EFK builds a more resilient system by excluding anomalous results and correcting errors such as:

- INS position error ;
- INS velocity error, 3x accelerometer bias, random velocity walk from random noise; and
- INS attitude error, 3x Gyro bias.

Gentner et al., 2018 stated a UWB and PDR complementary system could each achieve an accuracy of 0.2-0.5 m. In Liu et al. 2019 experiment, an EFK integrated UWB/PDR system; reduced PDR error by 74.5% and UWB by 43.5%. The outcome was an overall accuracy of 0.15m. An RMSE of ± 0.15m along the X and ± 0.18m along the Y.This is within the desired tolerance of the application, <0.5m position error along the X direction, 95% of the time.

NFC systems can be inspected periodically by an employee using a device to ensure the stored information is correct. If incorrect, the tag can be updated or replaced if broken. A broken tag does not affect the entire NFC infrastructure or positioning system. UWB and PDR are still available, creating constant availability and added resilience. IMU sensors create compensations for known sensor errors and perform range checks to detect failures (Groves, 2013).

Fault detection, integrity monitoring and checks can be incorporated into the solution by:

- positioning anchors in a room, so there are 5 UWB anchors (pseudo-ranges) available for fault detection or six for fault exclusion;
- consistency checks through redundancy: by increasing the number and spread of NFC tags system integration and therefore the position solution has more information than necessary.;
- zero-velocity updates (ZUPTs) could be introduced in EFK as pseudo-measurements. ZUPTs help in reducing error accumulation by resetting the velocity updates from the accelerometers;
- consistency checks and fault detection: using a four-axis IMU instead of three, monitoring integrity and fault detection by comparing readings, spotting failures and using other sensors; and
- Integrity monitoring using parallel solutions, standalone measurements can be compared to system outputs; results outside a determined threshold indicate sensor failure.

EFK limitations

The algorithm requires tailored tuning, compromising between convergence rate and stability. The estimated errors can be overestimated if the system's assumed input values and measurement noise are not realistic. Parameter selection is key to EFK's effectiveness if the values are too large; the uncertainties detected will be too large (Groves, 2013). The Tukey weight factor will not detect minor errors that go unnoticed, adding errors to corrections.

Design Justification

This section highlights the chosen technology and its suitability to the application requirements, whilst comparing them to other technologies. Table 5-9 displays industry examples of each sensor technology and characteristics such as power consumption, cost and dimensions. Summarising the figures in the tables produces an estimated cost of £240,000 for large museums and galleries and £475,000 for global ones. The estimation is not including installation and the salaries of the employees who would operate the system. Suppose it was to cost £100,000 (large) and £200,000 (global). The first-year cost will approximately be around £340,000 (large) and £675,000 (global), well within the proposed budget. The British Museum has 95 rooms; this was used as an estimate for global museums and galleries. In contrast, 48 rooms were used an estimate for large buildings.

A summary of Tables 6, 7, 8, 9 and 10 and the requirements of the application:

- a 1200 maH battery in the user equipment can supply enough power to all the sensors to last the required 12 hours;
- all sensors operate within the temperature constraints;
- UWB extends beyond the required range of 20m ($400m^2$, see Table 6);
- all sensors easily achieve the update requirement of >1Hz; and
- the total technology cost is within the £1.5M-£10.7M budget.

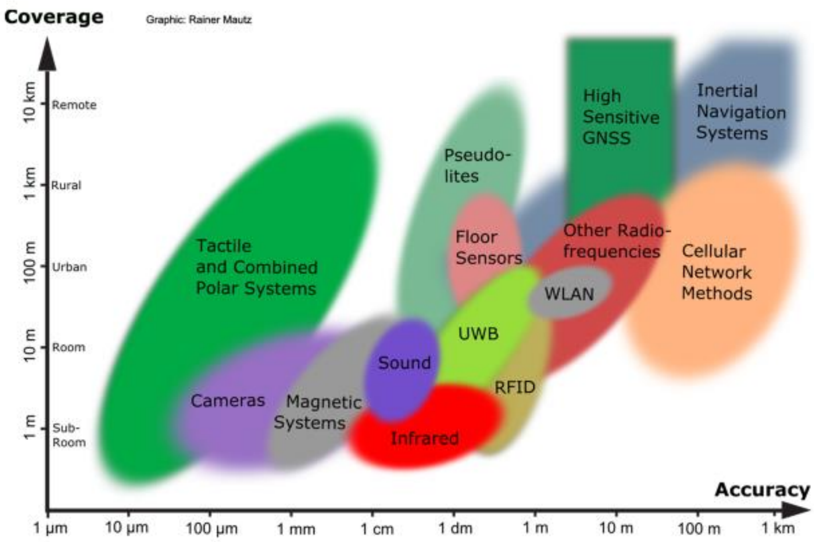


Figure 7 Accuracy and coverage of indoor technologies. Sourced : (Mautz, 2012)

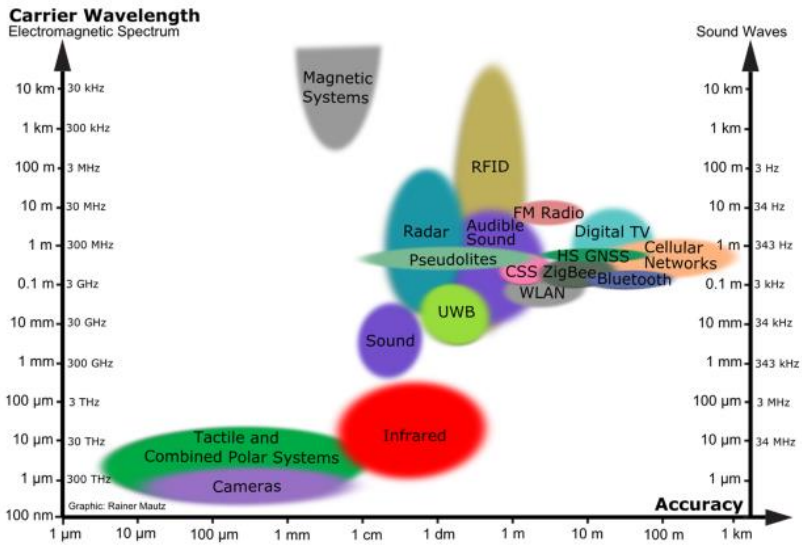


Figure 8 Carrier wavelength and accuracy for indoor positioning technologies. Source: (Mautz, 2012)

UWB Characteristics and Application Requirements

The Federal Communications Commission (FCC) limited unlicensed UWB signal power to -41.3dBM/MHz (see Figure 9). FC restrictions limit the range to 100 m, which is within the coverage requirements. It also creates a boundary between narrowband receivers, reducing signal interference. UWB can also penetrate concrete, wood and glass (Mautz, 2012). Penetration is a vital property; signal strength can be maintained when signal scattering and attenuation caused by obstructions are present. Positioning in NLOS conditions provides a further advantage of inter-room positioning: fewer anchors can be deployed, reducing cost.

UWB provides centimetre precision, whereas Bluetooth and Wi-Fi are opportunistic positioning technologies, positioning is not their primary design. This is reflected in their accuracy range being above the sub-metre requirement of the technology breaching the required tolerance (see Figure 8). Bluetooth and Wi-Fi would fail to achieve one of the primary and the secondary objectives; there is not enough accuracy for the two-metre social distancing buffer. It would generate false proximity alerts. Scalability can be achieved by adding more anchor points and tags. The unique time modulation between the tag and anchor and the lowered transmission power produces a secure solution (Nekoogar, 2005). Lowered probability of detection and interception increases system security.

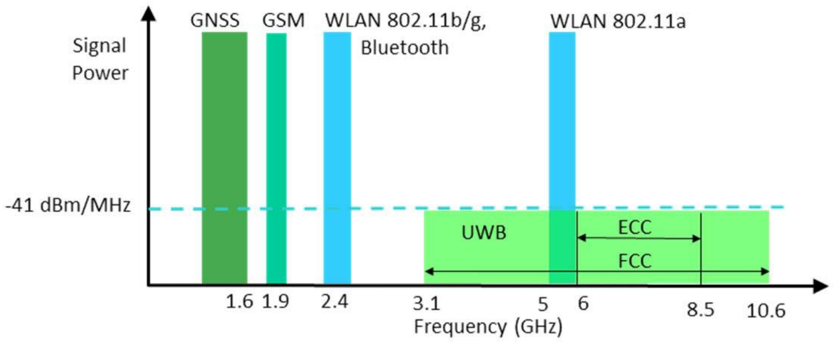


Figure 9 ***Radio Frequency standards of UWB and other technologies****. Source : (Mautz, 2012)*

Table 5 ***Summary of UWB Kit****. The figure shows characteristics that were highlighted as necessary in the requirement and actual product specifications. Source: (Sewio, 2021)*

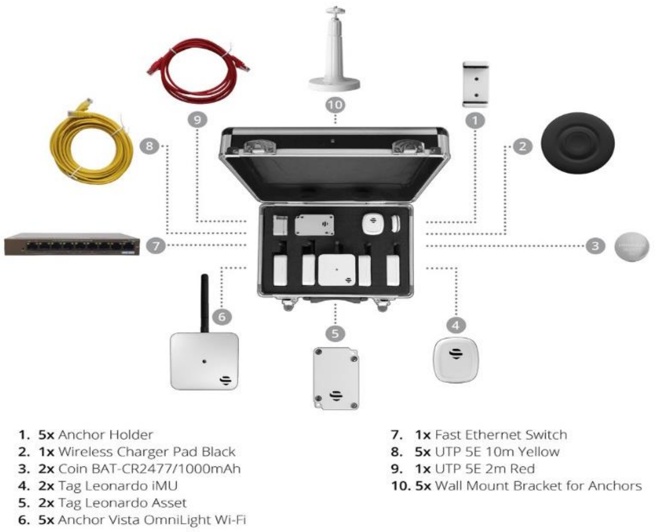


Figure 10 RTLS UWB Kit Wi-Fi Source: (Sewio, 2021)

RTLS UWB Kit Wi-Fi	
Costs	£2,600
Cost 48-95 rooms	£119,00- £247,000
Anchor dimensions	74 x 74 x 25mm
Anchor weight	72g
Power requirements	DC 5V, 500mA PoE Power Bank wireless rechargeable up to 5-year battery life
Devices (scalability)	<10 more than 10000
Coverage area	400m^2 (4,305 sq ft)
Operating conditions	0 - 60 °C
Backhaul	Wi-Fi and ethernet
RTLS Software (annual)	£3000
Tag refresh rate	100ms – 300ms

Table 6 ***Specification summary of a UWB tag****. The figure shows characteristics that were highlighted as necessary in the requirement and actual product specifications. (Decawave, 2016)*

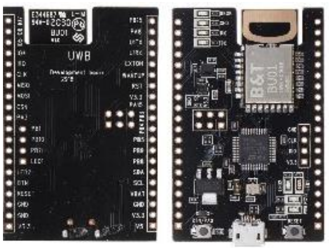


Figure 11 ***UWB transceiver.*** *Source: (Decawave, 2016)*

AI-Thinker® Wideband Indoor Positioning Module_Distance Measurement NodeMCU-	
Costs	£23.66
Cost 2000- 5000 units	£47,320-£118,00
Dimensions	35 x 55.5(±0.2)mm
Weight	~2g
Supply voltage	2.8V to 3.6V
Power consumption	160 mA
Operating temperature	-40°C ～85°C
Handheld device cost based on SIM Free Alba 4 Mobile Phone	
Costs	£30
Battery consumption	1200mAh battery capacity
Cost 2000-5000 units	£60,000-£150,000
Accuracy	Up to 10cm
Processor	1.2GHz quad core
Data rate	110 kbps, 850 kbps, 6.8 Mbps

NFC and Application Requirements

The proximal property of NFC greatly reduces the chance of signal interference. Conversely, infrastructure dependent, wired and wireless network technologies such as WI-FI, Bluetooth and UWB suffer a reduction in positioning accuracy. As NLOS, multipath, building geometry and density interfere with the path of electromagnetic waves. Security is also improved in the same way. GNSS, Wi-Fi and other technologies which require location based on signal transmission are more susceptible to invasion of privacy, corruption of data and theft.

Radio Frequency Identification (RFID) poses the same near field properties as NFC operating in the 13.56 MHz spectrum. For the nature of the application to read stored spatial coordinates, RFID is be equally suited. The shift of the market towards NFC technology played a significant roll in NFC being chosen over RFID. There is a potential for the visitors personal NFC enabled mobile device and a developed application to read tags and access information, similar to the user equipment.

Solely using NFC does not meet the objective of providing continuous real-time positioning. Its instantaneous nature designates it as a subsystem in the position solution. NFC tags have a long lifecycle (see Table 9) as they are passive and do not contain batteries or wear out due to use. Its affordable nature makes maintenance inexpensive as tags can easily be replaced and scalable; more tags can be added to extend the infrastructure.

Table 7 ***Specification summary of an NFC chip.*** *(NXP, 2019)*

Figure 12 ***NFC chip****. Source: (NXP, 2019)*

NT3H2211W0FT1X, NFC Forum Type 2 Tag	
Costs	£1.248(1) £0.47 (1000)
Cost 2000-5000 units	£940- £2,350
Dimensions	2 x 3mm
Power requirements	0.7V to 3.6V
Power consumption	40 mA can be powered by a coin cell~610 mAh
Weight	~1 g
operating conditions	- 40 °C up to 85 °C

Table 8 ***Specification summary of an NFC tag.*** *Source: (NXP, 2019)*

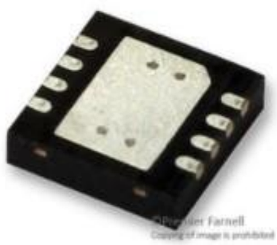


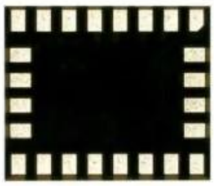
Figure 13 ***NFC tag. Source:*** *(STMicroelectronics, 2014)*

NFC Tag, SRTAG-D Series, Read / Write	
costs	£0.16 (1)
Cost 48-95 rooms	£76.8-£153.6
Dimensions	47 mm x 34 mm
weight	~1 g
Supply Voltage	2.7 to 5.5 Volts passive
Data rate	106 Kbps
Data retention	200 years
Endurance	1 million erase-write cycles
Security	128 bits passwords protection

INS and Application Requirements

Microelectromechanical systems (MEMS) are the primary technology for small consumer internal sensors. PDR accuracy over short distances range between 0.1%-20% (% of distance travelled) (Mautz, 2012). Gait detection for walking is accurate at 99.2% and running at 96.7 % (Liu, et al., 2019). Context detection in the application is paramount to produce accurate real-time tracking.

Table 9 ***Specification summary of a MEMs IMU. Source:*** *(STMicroelectronics, 2014)*

<table>
<tr><td rowspan="10">
Figure 14 MEMS IMU. Source: (STMicroelectronics, 2014)</td><td colspan="2">MEMS Module, iNEMO LSM9D Series, IMU</td></tr>
<tr><td>Costs</td><td>£5.628 (1) £4.68 (500+)</td></tr>
<tr><td>Cost 2000-5000 units</td><td>£9,360-£23,400</td></tr>
<tr><td>Dimensions</td><td>3.5x3x1.0mm</td></tr>
<tr><td>Voltage supply</td><td>1.9V to 3.6V</td></tr>
<tr><td>Power consumption</td><td>1.9mA</td></tr>
<tr><td>Operating conditions</td><td>-40 °C to +85 °C</td></tr>
<tr><td>Weight</td><td>~2g</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Output Data Rate (ODR)</td><td>952Hz</td></tr>
</table>

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