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The Complexity Problem in Future Multisensor Navigation and Positioning Systems: A Modular Solution

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Navigation and positioning system users are demanding greater accuracy and reliability in ever more challenging environments. This is driving a wave of rapid innovation with the result that multisensor integrated navigation systems will become much more complex. This introduces a number of problems, including how to find the necessary expertise to integrate a diverse range of technologies, how to combine technologies from different organisations that wish to protect their intellectual property, and how to incorporate new navigation technologies and methods without having to redesign the whole system. It also makes it desirable to share development effort over a range of different applications. To address this, the feasibility of a modular approach to the design and development of multisensor integrated navigation and positioning systems is analysed. Assessments of the requirements of different user communities and the adaptability of the different navigation and positioning technologies to different contexts and requirements are presented. Based on this, the adoption of an open interface standard for modular integration is recommended and the issues to be resolved in developing that standard are outlined.

KEY WORDS
1. Modular Navigation. 2. Integrated Navigation. 3. Multisensor Navigation. 4. Multisensor Positioning.

1. INTRODUCTION. Navigation system users are demanding greater accuracy and reliability in ever more challenging environments, such as dense urban areas, indoors, underground and underwater. There is more demand to maintain a position solution when global navigation satellite systems (GNSS) signals are subject deliberate jamming or incidental interference, which are becoming more prevalent (Thomas et al., 2011). High integrity (i.e., protection against unexpected large position errors) is also becoming important for a wider range of applications (Pullen et al., 2011).

In response to these more demanding requirements, navigation is undergoing a period of rapid innovation (Groves 2013b). New positioning methods demonstrated over the past three years alone include GNSS shadow matching (Wang et al, 2013), Doppler positioning using Iridium signals (Whelan et al, 2011), magnetic anomaly matching for road vehicles (Shockley and Raquet, 2012), cardinal heading updates for indoor navigation (Abdulrahim et al, 2011), Wi-Fi simultaneous localization and mapping (Faragher et al, 2012) and indoor positioning using Bluetooth low energy (Kalliola, 2011). More general trends include multi-constellation GNSS, positioning using short-range communication signals, miniature inertial sensors, camera-based navigation and use of 3D mapping. In principal, there are many different features of the environment that could be used for positioning (Walter et al., 2013).

To deliver the better performance that users demand and meet the needs of new applications, integrated navigation systems must incorporate these new innovations. The new positioning methods are generally designed to be used alongside existing technologies not in their place. Consequently, integrated navigation systems will become more complex. This makes the task of integrating the different subsystems much more challenging. Problems include how to find the necessary expertise to integrate a diverse range of technologies, how to combine technologies from different organisations that wish to protect their intellectual property (IP), and how to incorporate new navigation technologies and methods without having to redesign the whole system.

Until now, navigation and positioning user equipment designs have been bespoke, with a different combination of hardware and software developed for each application and user community, typically by a different manufacturer. For example, the integrated navigation systems for military aircraft, commercial ships, consumer cars and smartphones have all been developed separately. Each is designed to meet a particular set of user requirements and adapted to a particular context, defined as the environment in which the system operates and the behaviour of its host vehicle or user (Groves 2013a). However, in meeting the triple challenge of increasing complexity, more applications to serve and continuing cost pressures, it is time to question whether the bespoke approach to development is still viable.

This paper therefore analyses the feasibility of a modular approach to the design and development of multisensor integrated navigation and positioning systems that can meet the user requirements of multiple applications in multiple contexts. There are three main aims of this proposed approach:

- To minimise the costs of design, development and production by sharing hardware and software components across a wide range of product families;
- To ensure the interoperability of components provided by different organisations without requiring whole-system expertise or disclosure of IP;
- To enable easy reconfiguration to incorporate a new positioning technology or meet a new set of requirements.

The feasibility analysis comprises three parts. Section 2 compares the requirements of different user groups and applications, assessing their compatibility. Section 3 assesses each class of navigation and positioning technology to determine the extent to which the hardware and software may be designed to meet the requirements of a range of different applications. Section 4 then assesses how the hardware and software components of a modular navigation system may be integrated in a way that meets the interoperability and reconfigurability goals set out above, proposing an overall framework for this. A specific solution is not prescribed here as the details of any framework for combining technologies from many different suppliers must be determined collaboratively. Section 5 therefore proposes the realisation of modular integration through the development of open interface standards for exchange of navigation information between modules, summarising the tasks that must be undertaken to achieve this. Finally, Section 6 summarises the conclusions and topics for further investigation.

2. USER REQUIREMENTS.

The requirements for a navigation or positioning system depend as much on the needs of the user community as on the characteristics of the host vehicle. This assessment is therefore organised by user group. There are four main classes: consumers, professionals, researchers and the military. For each class, the requirements common to all applications are summarised and then the differences in requirements between applications compared. Conclusions are drawn on the scope to share hardware and software designs both within each user class and across classes, based on the compatibility of the different requirements.

2.1. *Consumers*. The key requirement for consumer positioning devices is the minimization of cost. This is achieved through large production runs, enabling research and development costs to be shared across many millions of individual devices. Minimization of size, weight and power consumption is also important with the latter achieved by powering up subsystems only as and when required. Performance requirements are secondary and are typically qualitative rather than quantitative. Thus, the position accuracy must be sufficient to

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enable map-aided route guidance, tracking of people and pets and various location-based services to function effectively. The reliability must be sufficient to avoid unduly annoying the user. Consumers generally accept that new technology does not always work as intended. However, they expect reliability to improve as a technology matures.

Consumers' performance expectations for positioning technology will increase with time. They will increasingly require a seamless position solution, available indoors and outdoors, and when stationary, walking, in a car, on a train, plane or ferry, or playing sport (El-Sheimy and Goodall, 2011). This could be achieved in two ways. The first is through the development of a multimodal navigation and positioning system, embedded within a consumer mobile device, which can handle a wide range of environmental and behavioural contexts. The second approach is to achieve seamless positioning collaboratively through the interaction between mobile devices, vehicle positioning systems and infrastructure-based tracking systems. Both approaches require some degree of cooperation between the suppliers of the various subsystems.

2.2. *Professionals*. For professional users, it is essential that navigation and positioning equipment meets a clearly defined set of performance requirements. For air and sea navigation, failure to meet performance standards compromises safety, whereas for surveying, a failure results in work having to be repeated, increasing costs and compromising schedules. Integrity is thus important. For most professional applications, size, weight and power requirements, though important, are less critical than for consumer applications. The main exception is tracking of assets and people, for which consumer-grade equipment is typically used.

User equipment costs of several thousand dollars can be justified when compared with the costs of insuring an airliner or ship or the savings in staff time that better equipment can bring. With user bases measured in the tens of thousands rather than tens of millions, research and development accounts for a large part of the equipment cost. Therefore by sharing designs across a wider range of application domains, there is substantial scope to reduce costs.

Different applications have different performance requirements. For air navigation, reliability (expressed in terms of integrity, continuity and availability) is most critical (Rife and Pullen, 2009), whereas for surveying, accuracy is more important (Rizos and Grejner-Brzezinska, 2009). This has led to very different design philosophies that are difficult to reconcile. A modular approach to design would enable common hardware components to be combined with software modules tailored to meet the relevant performance requirements. This approach has already been adopted for GNSS surveying equipment and could potentially be deployed more widely. Some hardware and software components could also be shared with consumer devices.

2.3 *Researchers*. Researchers comprise both those who use navigation and positioning equipment as a measurement tool and those working to advance navigation and positioning technology itself. Many of the former group are already well served by professional-grade user equipment. Tracking devices are available to support a range of research and development needs while GNSS surveying equipment is used for a wide variety of scientific applications, facilitated by the adoption of a standard format for recording measurement data, Receiver independent exchange (RINEX). This discussion will therefore focus on those researchers whose needs are not met by existing commercially available technology. Accuracy and update rate are typically more important than reliability; experiments can usually be designed to circumvent the limitations of the positioning techniques, while faulty data can often be discarded when the results are analysed. The importance of size, weight, power consumption and cost vary with the application.

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Researchers using navigation equipment for new applications may need to adapt the technology to meet their requirements. For example, studying the locomotion of wild animals requires the measurement of high dynamics by small, lightweight sensors with low power consumption (Wilson et al., 2013). However, not everyone wants to become an expert in navigation technology. Similarly, those developing new navigation sensors and techniques would like to assess their performance as part of an integrated system without having to become experts on every subsystem. Thus, the research community needs modular navigation and positioning technology that enables the easy modification of individual hardware and software components. Hardware can be shared with consumer and professional user equipment. However, the software would ideally be open source to enable easy modification and minimise costs. This is not necessarily compatible with the business models of the commercial companies supplying consumer and professional users. Therefore, the research community itself would have to develop this software resource.

2.4. *The Military*. For military applications, solution availability is the key performance requirement. There must be a useable position solution regardless of context. In particular, very high host vehicle dynamics and hostile jamming of GNSS and other radio signals must be tolerated. Some applications require indoor, underground or underwater operation. Consequently, there is great interest in using environmental features and signals of opportunity to maximise robustness (Miller et al, 2009). The Defense Advanced Research Projects Agency (DARPA) has proposed the term “all-source” to describe complex multi-sensor positioning and navigation systems (DARPA, 2010).

For most military applications, the accuracy required is a few metres, while the integrity requirement varies. Reliability is not critical for applications such as guided weapons and dismounted personnel, as an element of risk is assumed, but it is much more important for high-value platforms, such as ships and aircraft. Applications such as air-to-air refuelling and automatic landing of aircraft on ships require sub-metre positioning with a high level of integrity (Groves et al, 2008). Cost, size, mass and power consumption requirements also vary between applications; generally, the larger the host vehicle, the larger these may be.

The consumer model of a single device that is expected to perform both personal and vehicle navigation is unlikely to extend to the military. This is not only due to the differences in requirements. To maintain situational awareness, all military platforms, vehicles and dismounted personnel must have their own navigation systems which must communicate securely with each other. The communication links provide an ideal platform for cooperative (or collaborative) positioning which can enhance robustness in challenging environments through the sharing of information between peers (Grejner-Brzezinska et al, 2010). This requires all equipment to be mutually compatible, which would be facilitated by a common modular integration architecture.

There are number of key differences between military and civilian user requirements. The first is the military requirement for stealth. Vehicles and personnel must not emit signals that enable them to be detected by their opponents. Essential communications links use spread spectrum techniques and/or narrow beams to avoid detection. This places constraints on the use of active sensors such as radar and remote positioning techniques, whereby an object is positioned using the signals it emits. Secondly, military components must typically exhibit ruggedness in the form of greater tolerance to physical shock, temperature extremes and electromagnetic radiation, increasing their cost. A third military requirement is technological advantage over opposing forces. Consequently, many technologies developed under military funding are restricted in their use, so are not available for civilian applications until other countries have duplicated the technology. These restrictions have applied to many types of inertial sensor, including the new inertial sensor (and clock) technology that the Defense

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Advanced Research Projects Agency (DARPA) is investing in (Shkel, 2011). Finally, the military require the ability to jam signals used by their opponents without jamming their own signals, which is reflected in the current movement towards using separate GNSS spectrum for military and open-access signals. For all these reasons, military and civilian navigation hardware will largely continue to evolve separately. However, there is scope to share software modules and the overall modular framework.

3. TECHNOLOGY ADAPTABILITY.

In a modular navigation or positioning system, hardware and software must be designed to meet the requirements, environmental context and behavioural context of a range of different applications. This section assesses the extent to which this is practical, considering GNSS and other radio positioning technologies, inertial and magnetic sensors, and cameras in turn, followed by a brief discussion of other position fixing and dead reckoning technologies.

3.1. *GNSS*. The manufacturing cost of GNSS chipsets has now dropped sufficiently to enable high performance receivers to be manufactured at low-cost. This renders feasible a “universal” GNSS receiver that is suitable for all user groups and applications with the caveat that separate civilian and military versions may be needed. However, there remains a trade-off between performance and power consumption which makes it a challenge to reconcile the requirements of consumers and professional users. One option is a receiver design that may be reconfigured to meet the needs of different applications by varying the number of front ends in use, the sampling rates of the analog-to-digital converters and the number of correlation channels in use all of which affect the power consumption (Shivaramaiah and Dempster, 2011). The number of correlators per channel and their spacing, the tracking bandwidths, acquisition algorithm and positioning algorithm would also need to be adjustable. For the lowest cost consumer applications, the manufacturing cost of the front ends is significant. One way of addressing this is to produce a single-front-end core receiver chip to which additional front-end chips may be connected (Mattos, 2013).

A common GNSS antenna for all applications is not practical, however. For consumer applications, the antenna must be small and cheap, particularly for smartphones. For most professional applications, the antenna sensitivity, polarization discrimination and phase centre stability take priority, which requires a larger, heavier and more expensive antenna.

3.2. *Other Radio Positioning Technologies*. Different non-GNSS radio signals are used for different applications (Groves 2013a). Some examples include distance measuring equipment (DME) for aviation, enhanced long-range navigation (ELoran) for marine navigation, Wi-Fi for indoor and urban positioning, and Locata for land surveying. By combining a broadband antenna with one or more tuneable front ends with variable sampling rates, it is possible to construct a single set of hardware that can operate with many different types of positioning signals and signals of opportunity (Mathews et al, 2011). This device could also be used to receive GNSS. Because of its much lower frequency, Eloran requires a separate antenna and front-end. However subsequent signal processing can use shared hardware (Mattos, 2009).

3.3. *Inertial and Magnetic Sensors*. Inertial sensors that both exhibit high performance and are low-cost, small, light and low-power do not exist at present. A modular navigation system must therefore use different grades of sensor for different applications. However, for magnetic sensors, a common hardware design is feasible because the heading errors arising from magnetic model limitations, hard- and soft- iron equipment magnetism and

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environmental magnetic anomalies greatly exceed those arising from the sensors (Groves, 2013a).

Considering the processing algorithms for inertial and magnetic sensors, inertial navigation, accelerometer levelling and magnetic heading algorithms can operate with almost any sensors and in most environments. However, pedestrian dead reckoning using step detection, host vehicle motion constraints, zero velocity updates and zero angular rate updates all depend fundamentally on the behavioural context (Groves, 2013a). These context-dependent algorithms can substantially improve performance under the right conditions. Therefore, a truly universal approach to processing inertial sensor measurements must be context-adaptive, detecting the behaviour of the host vehicle or user and adapting accordingly (Groves et al, 2013c).

3.4. *Cameras.* A basic digital camera of the type found in any smartphone or webcam is useful for almost any navigation and positioning application. For some applications, it would be useful to supplement this with an infra-red camera. The hardware challenge lies in ensuring a camera is pointing in the appropriate direction, which is not always achieved by attaching it to the user interface, as is the case for smartphones. This leads to the question of whether the camera should be mounted separately, in which case the lever arm separating it from the other navigation sensors must be determined, or whether the rest of the navigation system should be attached to the camera, in which case the user interface is likely to be separate. In either case, power and data must be conveyed between the two parts of the system. In practice, multiple cameras, pointing in different directions and/or providing stereo imaging are both feasible and useful for many applications.

A camera can be used for both position fixing, by comparing image features with a database, and for dead reckoning, by comparing successive images to infer the user motion (Groves, 2013a). Determining how to process the images depends on the context; for example, the camera may be downward looking for air applications and forward looking for land navigation. For image-feature matching, there will be different databases, containing different classes of feature, for different environments. Note also that an approximate position solution is needed to determine which region of the feature database to search and, if necessary, what to download from a server. Finally, image-based navigation remains an active research topic and is more advanced for some applications than others. Therefore, different image-processing software will be required for different applications.

3.5. *Other Technologies.* Most other navigation and positioning technologies are application specific. For example, sonar and acoustic ranging systems are usually designed to work underwater, while wheel speed sensors are only applicable to wheeled vehicles. Radar and laser sensors may be used on a number of different vehicles. However, air, land and marine implementations are different and the cost, size, mass and power consumption of these sensors is too high for many navigation and positioning applications. The sensors must also be mounted in the right place on their host vehicles.

In a modular navigation system, application specific sensors could be incorporated on a plug and play basis if a suitable interface were to be provided. This could be based on the universal serial bus (USB) or Bluetooth. Depending on the overall system architecture, the information supplied could be sensor measurements, position and velocity information or ranges and range rates.

Map matching can be used for most land navigation applications and does not require additional hardware, other than for storing data. However, the implementations for road vehicles, trains and pedestrians are quite different (Groves, 2013a). Therefore, the context must be known for it to be implemented correctly.

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4. SYSTEM ARCHITECTURES. Despite the differences in requirements across and within the different user groups, there is a lot of scope to share both hardware and software across many different navigation and positioning applications. Therefore, the next topic to consider in this feasibility analysis is the overall architecture of a modular navigation system. Questions to address include:

- How can the re-use of hardware and software components across different applications be maximised?
- How can compatibility between components from different suppliers be ensured without extensive sharing of IP? and
- How can the flexibility of the system to handle new technologies and applications be maximised?

The hardware architecture, integration algorithms and system reconfigurability are discussed in turn.

4.1. *Hardware Architecture*. There are a number of different ways of constructing a modular navigation system depending on the trade-off between development and production costs. One approach is to adopt a standard core that is augmented with different peripherals for different applications. Figure 1 illustrates this. The hardware core could comprise a reconfigurable GNSS receiver, a reconfigurable general radio, low-cost inertial and magnetic sensors, a processor and memory. A variation on this is to use the processing capacity and memory of a host device. There could be a built-in camera and/or connectors for external cameras could be included. Different antennas would be connected for different applications and a series of interfaces provided for connecting application-specific sensors, as required. Higher quality inertial sensors could be connected via this interface or incorporated in higher performing versions of the hardware core.

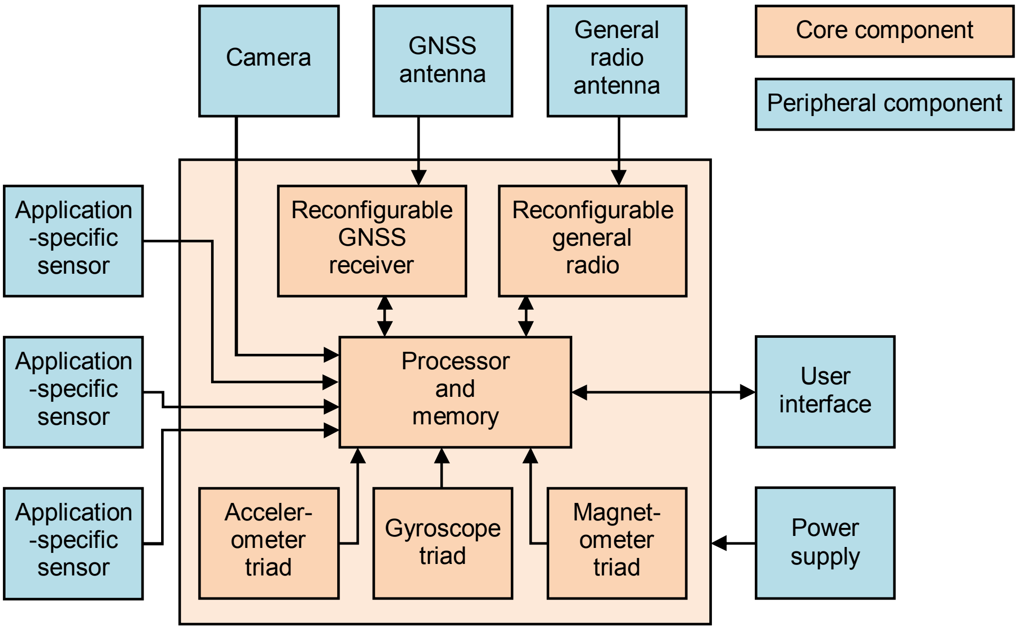

Figure 1. Core and peripheral hardware architecture.

An alternative model would be to design a set of interfaces that enables a range of different hardware (and software) modules to be connected together to meet the requirements of any navigation or positioning application. This would reduce the production costs for low-

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performance applications such as consumer devices. However, with a wider range of hardware modules, the overall development cost would be higher.

4.2. *Integration Algorithms*. Any multisensor navigation or positioning system needs integration algorithms to obtain the best overall position solution from the constituent subsystems (Groves, 2013a). However, there are a number of challenges that must be addressed. To obtain the best performance, integration algorithms must not only input measurements from a wide range of subsystems, but also calibrate systematic errors in those subsystems. However, designing the integration algorithms requires expertise in all of the subsystems, which can be difficult to establish in a single organisation. The move towards navigation systems with larger numbers of subsystems and modular designs that use different subsystems for different applications will make this problem worse.

An additional complication is that different modules in an integrated navigation system are often supplied by different organisations. These modules must work together. However, organisations can be reluctant to share the necessary design information as this is considered to be IP that must be protected. An extreme example of this is the smartphone: one company supplies the GNSS chip, another supplies the Wi-Fi positioning service, a third organisation supplies the mapping, the network operator provides the phone-signal positioning, a fifth company provides the inertial and magnetic sensors and a sixth company produces the operating system. Due to lack of cooperation between these different organisations, useful information gets lost. For example, GNSS pseudo-range measurements are not normally available to “app” developers and there can be gaps in inertial sensor data.

With new innovations constantly being introduced, a method is also needed for incorporating new positioning technologies and methods within integrated navigation systems without having to redesign the integration algorithms each time something is added.

Finally, and most fundamentally, an integrated navigation system is not truly modular if a bespoke integration algorithm is required for each application. For all of these reasons, a method of modularising the integration algorithm is required. One solution is to divide the integration algorithm into a universal integration filter module and a series of configuration modules, one for each subsystem. Figure 2 shows an example.

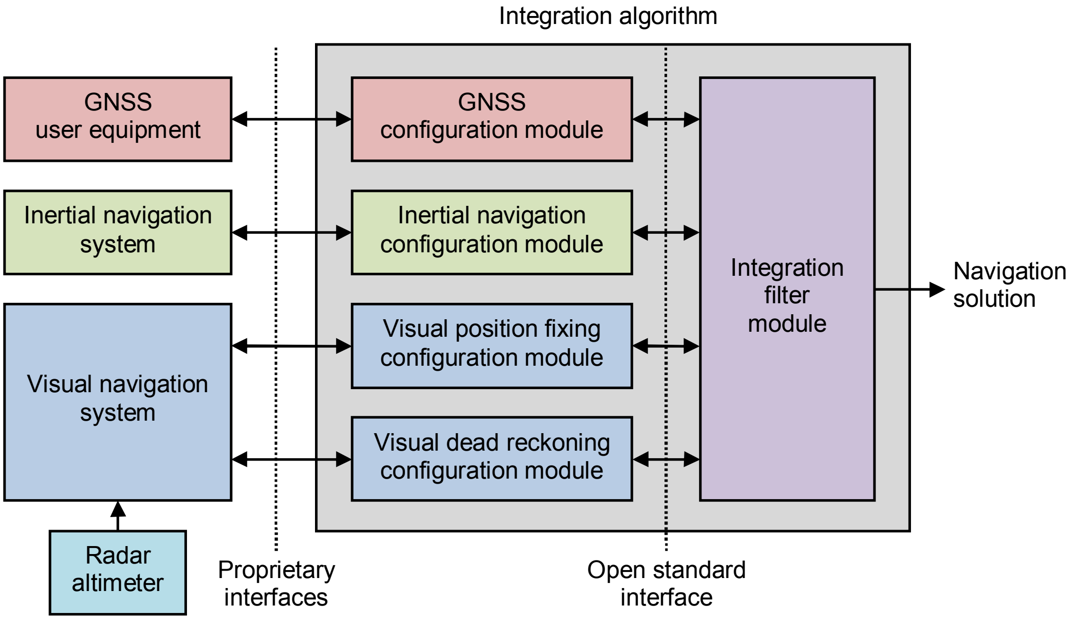

Figure 2. Example modular integration of GNSS, inertial navigation and visual navigation for an air application (each colour denotes a separate supplier).

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The integration filter module would be designed by data fusion experts and would accept a number of generic measurement types, such as position fixes, pseudo-ranges and inertial sensor measurements with associated metadata. Unlike conventional integration filters, a universal filter must reconfigure its measurement vector, state vector and associated matrices according to the measurements available. This capability is sometimes called ‘plug and play’ and a number of prototypes have already been developed (Hide et al, 2007; Penn, 2012; Soloviev and Yang, 2013). Table 1 lists the possible measurement types and their associated positioning methods. A truly universal integration filter should be able to support measurements in the position and velocity domain (i.e., loosely-coupled integration) and in the range and angle domain (i.e., tightly-coupled integration). It should also be able to support both total-state integration, whereby the navigation solution is directly estimated by the integration algorithm and error-state integration, whereby the errors of a reference navigation solution are estimated. The fundamental positioning methods and the different types of integration architecture are explained in Groves (2013a).

Table 1. Fundamental measurement types and their associated positioning methods.

Measurement type	Dead reckoning	Proximity	Ranging	Angular positioning	Pattern matching	Doppler positioning
Position solution (3D, 2D, or height only)	Yes	Yes	Yes	Yes	Yes	Yes
Multi-hypothesis position solution	No	Yes	Possibly	Possibly	Yes	No
Position likelihood distribution	No	Yes	Possibly	Possibly	Yes	No
Line fix	No	No	No	Yes	Yes	No
Velocity solution (3D, 2D, or vertical)[1]	Yes	No	Yes	Possibly	Possibly	Yes
Position and velocity[1]	Yes	No	Yes	Possibly	Possibly	Yes
Attitude solution (3D or heading only)[1]	Yes	No	Yes[2]	Yes	No	No
Position, velocity and attitude[1]	Yes	No	Yes[2]	Yes	No	No
Body-resolved velocity	Yes	No	No	No	No	No
Body-resolved displacement	Yes	No	No	No	No	No
Specific force[3]	Yes	No	No	No	No	No
Angular rate[3]	Yes	No	No	No	No	No
Ranges/pseudo-ranges[4]	No	No	Yes	No	No	No
Differenced ranges/ pseudo-ranges[4] [5]	No	No	Yes	No	No	No
Range rates/ pseudo-range rates	No	No	Yes	No	No	Yes
Azimuths or azimuths and elevations[1]	No	No	No	Yes	No	No
Azimuths with respect to body	No	No	No	Yes	No	No
Differenced azimuths[5]	No	No	No	Yes	No	No

[1] Resolved with respect to an external coordinate system, such as north, east, down.

[2] Requires an antenna array.
[3] Or the integral thereof.
[4] Differencing across receivers may be performed by the relevant configuration module prior. to input by the universal filter module.
[5] Differenced across transmitters or environmental features.

The integration filter could be an extended Kalman filter, an unscented Kalman filter, a particle filter, or a new type of data fusion algorithm. Different filter designs are suited to different applications. There are different ways of handling large uncertainties, unreliable measurements and irregular error distributions. Kalman filter-based estimation algorithms have maximum error tolerances, beyond which significant modelling errors can arise. For particle filters, there is a trade-off between the number of subsystem errors estimated and the complexity of the error distributions that can be handled. Overall, there is a three-way trade-off between robustness, processor load and precision.

The configuration modules would convert the subsystem outputs into the standard measurement types and provide the metadata necessary to integrate those measurements. This comprises the locations of transmitters and other landmarks, which subsystem errors should be estimated by the integration filter module and statistical descriptions of the measurement errors and subsystem errors, including their variances and the power spectral density of their time variation. This statistical information is essential to ensure correct weighting of the measurements and enable position uncertainty bounds to be computed. Thus, for example, to incorporate inertial sensor measurements, the inertial sensor specifications are required. For each measurement type, a standard set of subsystem errors that could be estimated would need to be agreed, such as biases, scale factor errors, temperature dependencies and range ambiguities. The correlation across multiple measurement streams of ranging biases due to clock offsets must also be specified. For each error type, both open-loop and closed-loop correction (Groves, 2013a) should be supported.

Each configuration module would normally be provided by the supplier of the subsystem to which it applies. The developer of a new navigation or positioning technique could incorporate their subsystem within an existed integrated navigation system simply by writing a configuration module for it; they would not need to become experts in sensor integration or the other subsystems. It is tempting for developers to produce configuration modules that provide oversimplistic and/or overoptimistic descriptions of their subsystems. Therefore, some form of certification procedure would be needed to enable other organisations to trust a new module.

For total-state integration, a dynamics model configuration module would also be needed to provide the universal filter with information on the host vehicle (or pedestrian) dynamic motion.

The key to the success of this modular integration approach is the definition of the interfaces between the universal filter module and the configuration modules. With a clearly defined and open interface standard, it should be possible to combine any integration filter module with any set of configuration modules without the module designers needing to know the inner workings of the other modules. This leaves organisations free to protect the IP within their own modules. However, it is still necessary to ensure that the filter module is suitable for the application in question. Furthermore, in practice, a filter module may not be designed to support every measurement type and there will be limits to the sizes of the errors it can handle. The interface standard must therefore incorporate a capability specification for each filter module and a protocol should be developed for handling mismatches between the measurements and filter module. A certification process would also be needed to ensure that the filter module actually has the capabilities it claims. However, it is primarily the responsibility of the overall system designer to ensure that a suitable filter is selected.

4.3. *System Reconfigurability.* In a modular navigation system, hardware and software modules would be expected to operate under different environmental and behavioural contexts for different applications. The optimum design of the signal processing algorithms for GNSS and other radio positioning systems depends on the dynamics and reception conditions. Different image-based navigation and positioning algorithms are also suited to different environments and system dynamics, while the integration algorithm's dynamics model will always depend on context. A modular navigation and position system must also be able to adapt to the differing user requirements of different applications, such as accuracy, integrity, solution availability, update rate and power consumption.

Therefore, a modular navigation system must be reconfigurable. This can be achieved by adding a system control module that specifies the context and user requirements. This is then passed via the open-standard interface to the configuration modules which configure both the integration filter module and the subsystems themselves accordingly. Some subsystems will require different processing algorithms to be selected for different contexts and/or requirement sets. It may even be necessary to activate or deactivate subsystems according to the context.

The requirements should also be input directly to the filter module. In practice, different filter modules are likely to be needed, depending on whether high accuracy, high integrity or high solution availability take priority. This is because different design philosophies have historically been applied to meet these different sets of user requirements and significant effort would be required to reconcile them.

For applications, such as consumer navigation, where the context changes as the system is used, this can be detected using the available sensors and the system reconfigured accordingly. This is known as context-adaptive navigation (Groves et al, 2013c). Many navigation and positioning systems must also be able to switch between the requirements of different applications. For example, a consumer device may be used for navigation which requires continuous positioning, for tracking which requires position updates at regular intervals, and for location-based enquiries which only require single position fixes. Similarly, a single professional positioning device might be used for surveying static points, for setting out which requires the system to be moved until the desired location is found, and for controlling construction machinery which requires continuous positioning.

Figure 3 shows a suitable system architecture for a context-adaptive multi-application reconfigurable navigation or positioning system. Note that further research on context adaptivity and integrity frameworks for complex multisensor systems is needed before system reconfigurablility can be realised in full.

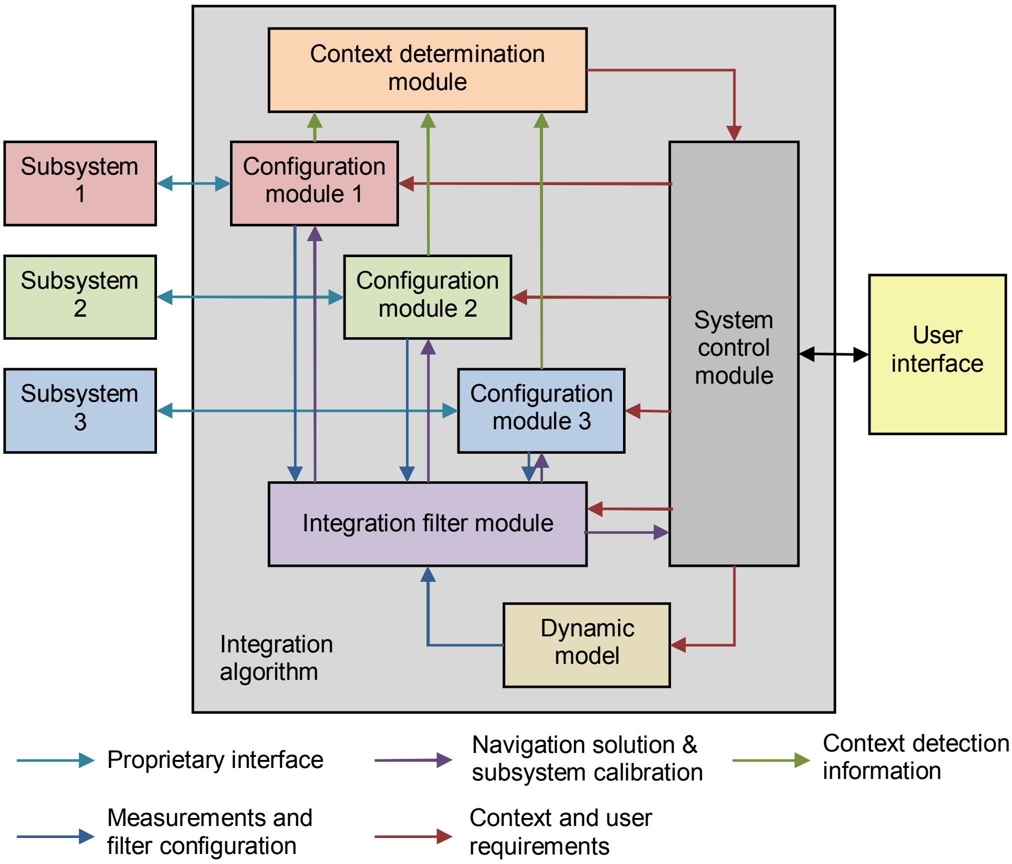

Figure 3. System architecture for a context-adaptive multi-application reconfigurable navigation system (each colour potentially denotes a separate supplier).

5. REALISATION OF MODULAR INTEGRATION. In order to implement modular integration beyond the research laboratory, an open-standard interface between the modules must be agreed. This standardization initiative must be as inclusive as possible as the development of multiple competing standards defeats the core objectives of modular integration. An international effort encompassing many different technologies, applications and user communities is thus required. Figure 4 depicts a suitable development process. To encourage organisations to adopt the standard, a set of demonstration modules, based on the test modules, should be made available to all interested parties at minimal cost. These demonstration modules would provide a baseline to which the other organisations could then add their own modules, some on a commercial basis and others on an open-source basis.

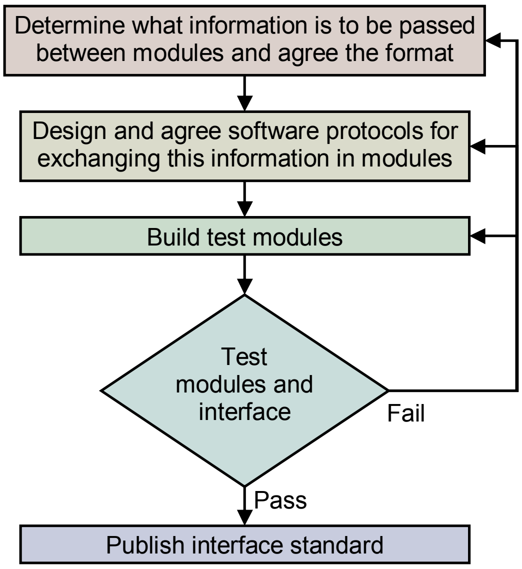

Figure 4. Development process for an open modular integration interface standard.

A key part of the standardization initiative is to agree on definitions of the information to be passed between the various modules shown in Figs. 2 and 3. The following parameters should be relatively straightforward to define, based on current knowledge:

- Units, axis conventions and coordinate systems (noting that Cartesian, curvilinear and local coordinate systems must all be supported);
- Measurement types to be supported by the universal filter module;
- Subsystem systematic errors for each measurement type that may be modelled as states, including system dynamics and stochastic models;
- Representation of measurement error statistics, including time correlation and correlation between measurements;
- Representation of time synchronization errors between subsystems and between groups of transmitters in passive ranging systems;
- Conventions for expressing requirements for accuracy, update rate, solution availability, processor load and power consumption.

Further research will be needed to define:

- Conventions for expressing integrity and continuity requirements, noting that different frameworks may be needed for different applications;
- Representation of the outer limits of statistical distributions for integrity monitoring;
- A convention for expressing a hierarchy of user requirements in the event of conflicts;
- A convention for expressing the maximum tolerances of the integration filter to large subsystem errors;
- Categorization and definitions of environmental and behavioural contexts, as explored in Groves et al (2013c);
- Determination of a context detection framework, including where to perform it, which subsystem measurements to use and how to express uncertainty.

Given this need for further research, a full standardization of reconfigurable modular integration is not yet feasible. A phased approach is therefore recommended, starting with a basic concept of modular integration that supports the main measurement types. Additional measurement types, context adaptability and integrity frameworks could then be added in later phases.

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6. CONCLUSIONS AND FUTURE WORK. The requirements of a range of consumer, professional, research and military navigation and positioning applications have been compared and the flexibility of current and projected navigation and positioning technologies has been assessed. Based on this, it is concluded that a modular approach to multisensor navigation and positioning is feasible and a system architecture has been proposed that enables:

- Research and development costs to be shared across a wider range of product families;
- Multiple subsystems to be integrated without the need for whole-system expertise within a single organisation;
- Hardware and software produced by different organisations to be combined without the need to share intellectual property;
- New navigation and positioning technologies and methods to be added without having to redesign the whole system.

In order to implement this architecture, the phased development of an open interface standard for communication between modules is recommended. To support the later phases of this development, further research is needed to develop an integrity framework for complex multisensor systems, establish standards for context-adaptive positioning and determine the performance limits of different integration filters when subsystem errors are large.

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