Integrating Self-Health Awareness in Autonomous Systems

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Abstract

One enabler for unmanned, autonomous system operation is mission awareness. Three components comprise mission awareness: knowledge of mission objectives, internal self-situational awareness, and external self-situational awareness. Mission objectives include both high level mission goals and any details operational requirements. Internal self-situational awareness entails knowledge of platform health and capability. External self-situational awareness encompasses knowledge of external resources (supplies, supervisors, or collaborators) as well as threats that can adversely affect system performance. An unmanned autonomous system must be able to translate mission objectives into actions and assess the impact of its internal and external state on its ability to execute the actions necessary to accomplish the mission objectives. If the combination of the internal and external state will not permit the system to achieve its mission objectives, the autonomous control system must revise the mission plan and possibly notify supervisors and collaborators (human or machine). This paper describes an approach to the integration of information an autonomous health monitoring system with a vehicle's autonomous controller. A behavior based, autonomous intelligent control system architecture developed for autonomous underwater vehicles is used to integrate both internal-self situational awareness, and autonomous control. The scalability of the architecture simplifies the addition of a hierarchical supervisor that can communicate with other collaborators to revise mission plans in the event of changes in the internal or external situation.

Introduction

In order to achieve higher levels of autonomous operation, unmanned vehicles will require autonomous control systems capable of adapting to unanticipated operating conditions. Autonomous system research and development has traditionally addressed the representation of the external operating environment as part of the autonomous control system. An accurate representation of the internal state of the system – including the health of critical subsystems – is also required for complete self awareness. By integrating knowledge of the health and capability of critical subsystems into the intelligent control system for an autonomous vehicle, the system can react to both external and internal changes. The system must be capable of using internal and external situational awareness to determine whether current capability exceeds current and anticipated demands on the system. If capability cannot meet of exceed demands, the system could become damaged or incapacitated. For a truly autonomous system, we cannot assume that a human operator can intervene or rescue the system; hence levels of damage or incapacitation that would be considered repairable or recoverable in a manned system may be fatal in an autonomous system.

Internal self-situational awareness implies that the autonomous control system not only knows the health and performance characteristics of critical components or subsystems, but can also the impact of the health and performance characteristics on the platform's ability to meet current demands. Assessing whether current capability exceeds mission demands, however, requires two pieces of information: knowledge of current health and performance, and knowledge of the expected demands on the critical components and subsystems. While many researchers have focused on developing tools and techniques for diagnosing problems in mechanical and electrical systems, determining the loads and demands on critical components and subsystems based on the planned mission or operation is itself a nontrivial problem.

The ability to respond to unanticipated changes in system health and performance is important not only for single or standalone autonomous systems, but also for teams of collaborating autonomous systems or mixed teams of autonomous, human-in-the-loop and human-on-the-loop systems. By sharing information on individual system health and capability, a collaborating team of systems can optimize usage of communal resources and adjust roles and responsibilities of individual team members to insure mission success.

Information on the health and capability of critical subsystems can be integrated into an autonomous control system in a number of ways. This paper describes an approach to integrating health monitoring for critical components and subsystems into an autonomous control system wherein the health monitoring system functions as an autonomous system which collaborates with the platform control system. The integration of the health information into the autonomous control system is demonstrated using a behavior-based autonomous intelligent control system architecture used by the Applied Research Laboratory in autonomous underwater vehicle applications. The application of integrated health monitoring and autonomous control is demonstrated in a simulation of two autonomous underwater vehicles executing a joint search mission. The application of integrated health monitoring and control is also described for an autonomous ground vehicle platform under development at the Applied Research Laboratory.

System Health Monitoring for Self-awareness

Automated system health monitoring involves the application of sensors, analysis, data fusion and automated reasoning to estimate the health and track the degradation of a system. A top-level view of system health monitoring is shown in Figure 1. Demands and loads are driven by mission requirements at the platform level and propagate down to the material level. Simultaneously, the degradation, and ultimately the failure, of components and subsystems starts at the material level and propagates up to affect operational capability. The monitoring system must detect and isolate component degradation and impending subsystem failure then generate appropriate alerts to autonomous control systems, operators, asset managers, and maintainers [1].

Figure 1 also shows the application of sensing, modeling and reasoning to system health monitoring. Data from sensors are processed and fused with other commensurate or non-commensurate sensor data. The detected state of the system is compared to historical data or system models to predict the remaining useful life of the component based on the observed evolution of the fault. Automated reasoning techniques are applied to determine the impact of the identified system state and remaining capability on the current or planned mission and convert that knowledge into useful information for the autonomous control system, operator or other information customers.

The costs associated with sensors and data acquisition systems are small compared to the cost of the platforms and payloads. Another key monitoring system component, the communication bandwidth required to transport data and information, however, can be expensive – both literally, in the cost of communications system requirements, and figuratively, in terms of opportunity costs if payload sensor communication bandwidth must be sacrificed for monitoring sensor data. Hence, the monitoring system must employ smart sensors and operate with its own autonomy to provide the platform autonomous intelligent control system or mission supervisor with high level information as opposed to raw sensor data. An architecture for monitoring system health

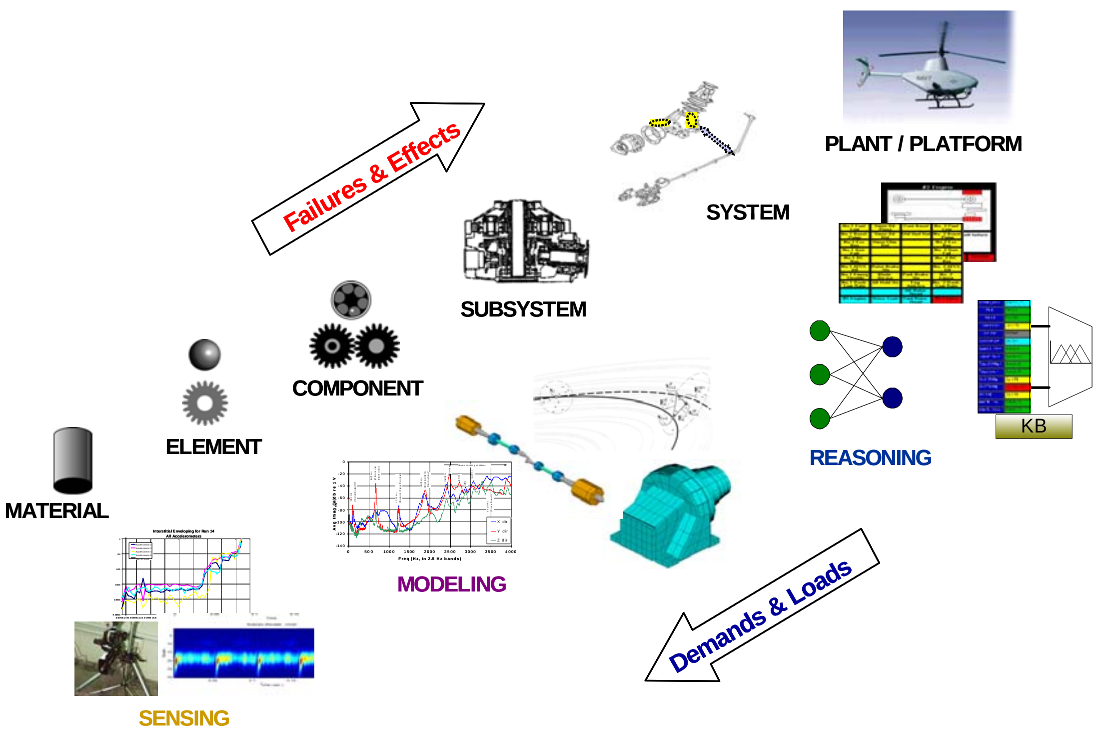

Figure 1 Demands and loads flow down from the platform level to the material level; degradation and failure propagate from the material level to the platform level.

to provide self-situational awareness is shown in Figure 2. The health monitoring system architecture uses a hierarchical organization of distributed nodes to process raw data and assess health and condition at the components, subsystem and system levels. This architecture can be implemented using a combination of physical (hardware and software) and virtual (software only) processing nodes.

At the lowest level, sensors monitor signals that provide indicators of system health and performance. At the next level in the health monitoring system data from multiple sensors associated with a particular subsystem are fused to improve detection of faults and reduce false alarms. At the next higher level, health information from multiple subsystems is fused to assess the health and condition of entire systems. Information can flow both ways and laterally between subsystem or system monitoring nodes to permit health assessment in the context of subsystem and system interactions. At the highest level, knowledge of system health is available for mission management and as an input to the autonomous control system.

The hierarchical health monitoring system architecture shown in Figure 2 has two advantages: it reduces the bandwidth required to get health information to the user (human or autonomous control system) by processing the raw sensor data, and it eliminates the requirement that the autonomous control system also be capable of performing the processing, fusion, and reasoning tasks associated with determining the health and capabilities of the subsystems from the sensor data [2]. Depending on the type of sensor, these signals may be sampled at 10's or 100's of kHz in order to provide early indicators of system degradation. While parameters such as temperature change rather slowly and lag changes in system health, parameters such as vibration can provide earlier indications of component degradation. Detecting early indicators of a change in system health, however, typically requires extracting high features associated with high frequency components of the measured vibration signals. The use of intelligent sensor nodes and a hierarchical architecture reduces 100's of kilo bytes of raw data to 10's of bytes of high level health information, a 10^4 reduction in bandwidth requirements.

Autonomous Intelligent Control Architecture

A behavior-based, autonomous intelligent control architecture is used to integrate internal and external self-situational awareness and execute the desired mission. In fact, the same architecture is used within the health monitoring subsystem to provide internal and external self-situational awareness. The use of a common autonomous system architecture eases the task of integrating system monitoring with control to provide autonomous vehicle management.

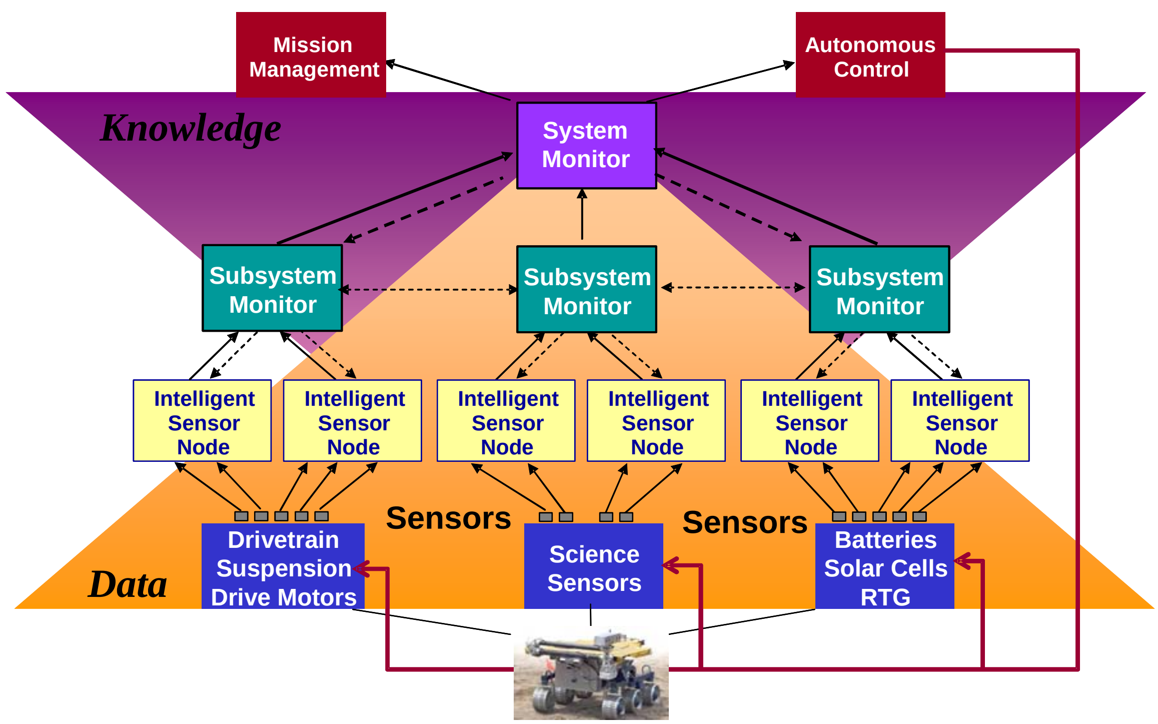

Figure 2 Hierarchical architecture for system health monitoring.

The Applied Research Laboratory has developed, demonstrated and deployed systems based on an autonomous intelligent control system (AICS) architecture in a number of applications [3-4]. The core of the AICS architecture, depicted in Figure 3, consists of a perception module and a response module. The perception module processes sensor information, commands, and messages to provide situational awareness for the controller. Depending on the source of the inputs to the perception module, the "situational awareness" may be internal, self-situational awareness, external situational awareness, or a combination of the two. The perception module determines which behaviors should be activated to respond to the current situation. The response module accepts the behavior recommendations of the perception module and considers the necessary actions within the context of the current mission plan.

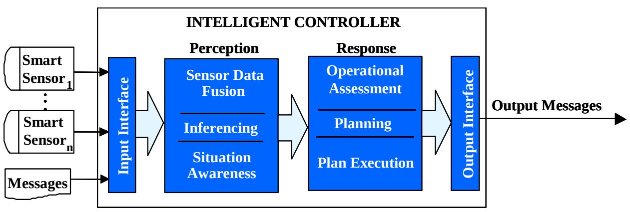

Figure 4 Autonomous Intelligent Control System architecture.

The perception module creates an internal representation of the world external to the AIC that is relevant to its mission using the processed input data and messages from other AICs or human operators/collaborators. This representation constitutes the AIC's "worldview" and serves as the basis for the generation of operational reactions through the response module. It is constructed from a finite, fixed collection of "representational classes" (RCs) created by the designers to specify the types of things the perception module can recognize. For example, data from target-acquisition sonar systems in underwater systems would be used by the perception module to build tracks on objects being detected; these tracks would be instances of an RC with a descriptive name, such as "Track." In order to accommodate the integration of health information, the control system should be designed to recognize health as a representational class.

Integrating Health Monitoring Into Autonomous Systems

Designers have a number of choices when integrating health information into an autonomous system. Health information can be integrated in the form of low-level sensor data by providing data from sensors mounted on critical components or subsystems directly into the autonomous control system. At the other extreme, health information can be integrated as high level information on the capability of critical components or subsystems. The latter approach reduces the bandwidth required for the transport of health-related information which can become especially important in multi-vehicle systems where off-platform communication bandwidth may be limited. The latter approach also decouples the design of the health monitoring system from the control system design and reduces the computational burden on the control system if extensive processing is required to extract system health from the sensor data.

One of the strengths of the AICS is the flexibility afforded the system through messages that allow one controller to communicate with another. Through these messages, multiple controllers, configured in parallel or in a hierarchy, can collaborate and effect changes in the overall mission plan. The application of the AICS architecture for internal situational awareness, external situational awareness and mission supervision is depicted in Figure 4. Three control blocks are arranged in a hierarchical architecture so the mission supervisor accepts inputs in the form of messages from subcontrollers providing internal and external situational awareness. The mission supervisor can communicate with digital or analog control systems for a specific platform subsystem to carry out specific actions or may communicate with another autonomous controller for particular subsystems (such as an autonomous propulsion system).

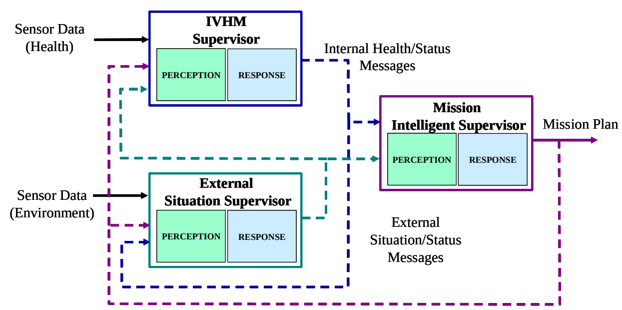

Figure 3 Application of multiple AICS for integrated system monitoring and control.

The architecture shown in Figure 4 has been demonstrated in simulation in a collaborative exercise between two autonomous unmanned underwater vehicles. The two vehicles were tasked to perform a collaborative surveillance mission. When the internal health supervisor for one vehicle detects that the power subsystem is loosing capacity, its mission supervisor sends a message to the supervisor for the other platform. The respective mission supervisors reallocate mission responsibility for each platform to still accomplish the overall mission despite degraded capability in one platform.

Figure 5 shows the tracks of the two vehicles. The vehicle on the right experiences the power system fault and the vehicle supervisor onboard the other vehicle (the vehicle on the left in Figure 5) adapts it's mission to cover a larger search area and make up for the degraded capability of the other vehicle.

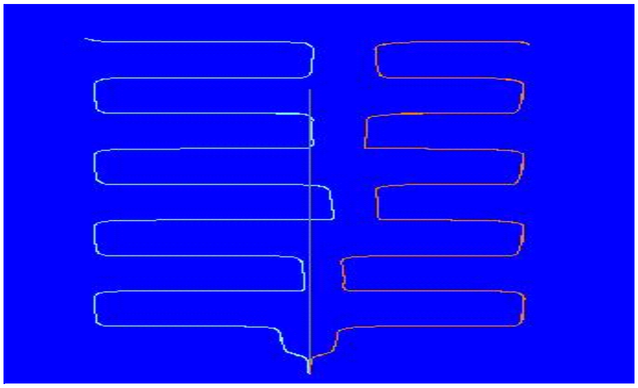

Figure 5 Simulated search tracks for two collaborating vehicles with shared health

A key issue in such multi-vehicle systems is the level of communication between individual vehicles. Although many possible configurations exist, there are three architectures that are worth considering:

- No direct communication
- All communication routed through a supervisor
- Fully integrated communication among peers

In the first communication architecture, there is no direct communication between individual vehicles. The only way one vehicle knows the health and capability of the other is by interference through observing the other vehicle's behavior. This fails to take advantage of self-situational awareness capability on the other vehicle since each vehicle is forced to assess it's health and performance as well as the health and performance of the other vehicles.

In the second communication architecture, each vehicle can communicate with a designated supervisor but not directly with other peers. This insures that there is always a supervisor with knowledge of the health of all vehicles. The supervisor is therefore responsible for changing the overall mission or roles of the individual members based on the health and capability of all of the assets. One disadvantage of this communication scheme is a lack of robustness in the event of damage or loss of the supervisor.

The third option can be implemented in a broadcast scheme where each vehicle publishes updated information on it's health and capability to the other vehicles or in a scheme where individual vehicles can request the health and performance information for all or a subset of the other vehicles. This method of communication provides the greatest flexibility since the other options described above can actually be implemented under this configuration. It allows for a supervisory-type structure with a fixed supervisor but also allows the possibility that another vehicle can assume the supervisor role in the event of damage to the existing supervisor. This communication scheme also permits more swarm-like tactics where each vehicle makes it's own decisions based on knowledge of the health and capabilities of it's neighbors. In the absence of a central supervisory or planning entity, the behavior of the collection of vehicles emerges from the combined efforts of the collective.

A complete dissertation on the advantages and disadvantages of centralized versus decentralized communications within a swarm or team of autonomous vehicles is beyond the scope of this paper. It is clear, however, that sharing of raw sensor data related to the health and performance of an individual platform is undesirable. The use of embedded health monitoring systems, however, condenses that information into very compact messages that can be accommodated within existing communication bandwidth restrictions. The use of the intelligent control architecture described above facilitates sharing information from one platform to another through the inclusion of messages between controllers. Because the controllers can be peers (operating at the same functional level within controllers on different vehicles) or hierarchical (vehicle to supervisor or vice versa) the autonomous intelligent control architecture can be applied in any of the three communication architectures.

Autonomous System Demonstration Platform

ARL has constructed a small ground vehicle platform for testing and demonstrating autonomy concepts. The platform, shown in Figure 6, is built on the chassis from a radio-controlled, off-road truck. The testbed was designed to accommodate a flexible configuration of sensors for a variety of applications. The system block diagram is shown in Figure 7. The current configuration includes a digital GPS, a combination compass and magnetometer, and an ultrasonic range finder for navigation. An IR camera and the ultrasonic rangefinder are mounted on a pan and tilt to simulate mission specific sensors. A rear pan and tilt with a second IR camera and range finder are planned for the rear of the vehicle.

The autonomy testbed described in Figure 6 and Figure 7 is being used to test and demonstrate the concepts described in this paper. In particular, the vehicle includes an integrated vehicle health monitoring system that monitors battery health monitoring. The health monitoring system provides the autonomous intelligent control system with an assessment of the battery state of charge and state of health. The state of charge determines the remaining system capability during the current mission or charge cycle. The battery state of health provides a prognostic capability and determines the capacity during the next and successive missions or charge cycles.

The health monitoring system provides the battery health information to the autonomous intelligent control system via high-level messages. The autonomous intelligent control system uses the information to adjust the mission plan to insure that the system returns to a location with battery recharging capability. The health information is also shared with collaborating autonomous systems to adjust individual mission plans to complete as much of the higher-level mission as possible with the reduced capability of an individual platform.

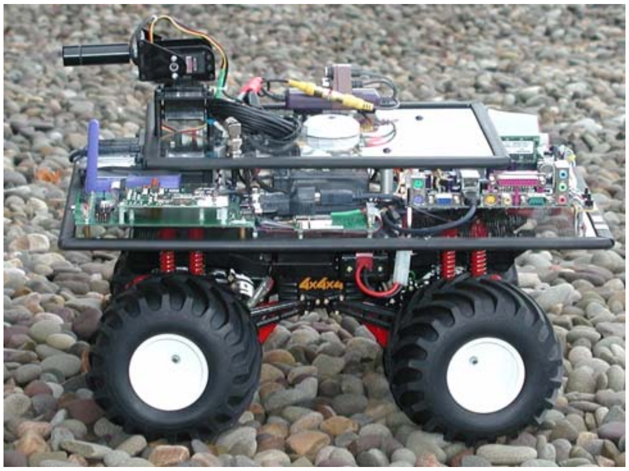

Figure 6 Photograph of ARL/PSU ground vehicle autonomy testbed.

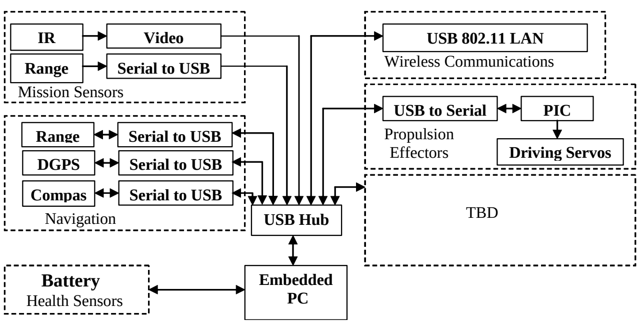

Figure 7 Functional block diagram of ARL/PSU ground vehicle autonomy testbed.

Conclusion

In order to achieve high levels of safety and mitigate mission risk, unmanned systems will require self-situational awareness and autonomous decision and response capability to respond to unplanned events, system degradation and failure. The Applied Research Laboratory has developed and demonstrated both system health monitoring and autonomous intelligent control systems for a variety of platforms and applications. The integration of these technologies provides an enabling capability for autonomous systems and has been demonstrated in simulations of collaborating autonomous underwater vehicles and using an autonomous ground vehicle testbed.

Acknowledgements

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