Dynamic Data Driven Analytics for Multi-domain Environments

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ABSTRACT

Recent trends in artificial intelligence and machine learning (AI/ML), dynamic data driven application systems (DDDAS), and cloud computing provide opportunities for enhancing multidomain systems performance. The DDDAS framework utilizes models, measurements, and computation to enhance real-time sensing, performance, and analysis. One example the represents a multi-domain scenario is "fly-by-feel" avionics systems that can support autonomous operations. A "fly-by-feel" system measures the aerodynamic forces (wind, pressure, temperature) for physics-based adaptive flight control to increase maneuverability, safety and fuel efficiency. This paper presents a multidomain approach that identifies safe flight operation platform position needs from which models, data, and information are invoked for effective multidomain control. Concepts are presented to demonstrate the DDDAS approach for enhanced multi-domain coordination bringing together modeling (data at rest), control (data in motion) and command (data in use).

Keywords: Dynamic Data Driven Applications Systems, Multi Domain data analytics, Fly-by-Feel avionics

1. INTRODUCTION

Data science has become a recent trend in engineering, business, and medical applications, among others. Data science is integral to the advancements in artificial intelligence (AI), machine learning (ML), as well as information fusion [1]. Such developments in information fusion have moved from surveillance applications from video and text analytics [2], towards that of the internet of things (IoT) [3, 4], multidomain applications [5], and battle management [6]. Multidomain applications likewise follow from various approaches to layered sensing [7, 8], where each layer represents data and information from different domains of space, air, ground, and sea as shown in Figure 1. Methods for combining sensing include: data (1960's), sensor (1980's), information (1990's), and multi-intelligence (2010's) information fusion; widely adopted from the Data Fusion Information Group (DFIG) process model [9, 10], as shown in Figure 2.

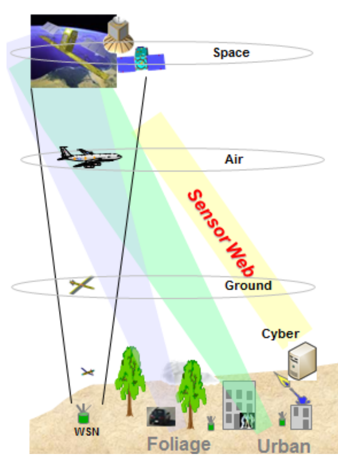


Figure 1 – Layered Sensing

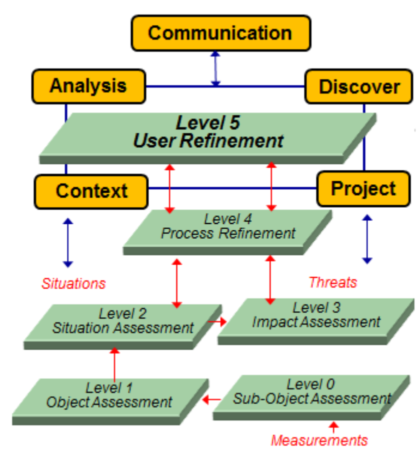


Figure 2 – Data Fusion Information Group model.

To enable the multidomain operations, examples include (1) space: satellite health monitoring and communication [11], (2) air: avionics control [12]; (3) ground: sensor fusion assessment [13], (4) sea: maritime awareness [14], (5) underwater: submarine navigation [15], and (5) cyber security [16]. Information management and data visualization help provide command and control [17]. With the plethora of information available, the big data elements: volume, velocity, variety, veracity, and value need consideration [18]. Hence, multidomain requires (1) command and control (e.g., tracking), (2) cyber security (e.g., health monitoring), (3) connectivity and dissemination (e.g., communications), and (4) processing and exploitation (e.g., remote sensing) to support various users [19] over contested environments [20] using context [21]. DDDAS can support multidomain applications through: (1) instrumentation methods, (2) real-world applications, (3) modeling and simulation, and (4) systems software [22, 23], as shown in Figure 3.

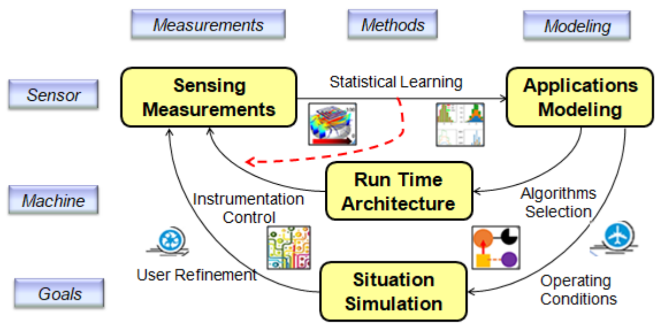


Figure 3 – Primary DDDAS components.

DDDAS developments in deep manifold learning [24], nonlinear tracking [25, 26], and information fusion [27, 28, 29]; show promise for advanced avionics assessments. For multidomain operations, there is a need for information management, feature sensing, and data analytics. Information management includes the types of data and signals being routed in the network for coordinated control and sensing. Key elements of information management include ontologies, data base access, and graphical networks [30]. Feature sensing results from images (e.g., multispectral imaging [31]) text, and actuators. Data analytics for multidomain includes space, air, and ground, but also responses to threats such as signals jamming, spoofing, and contamination.

Together, the large data needs to be visualized over the entire data space. The concept of a user-defined operating picture (UDOP) allows support operators to interact with the data for effective and efficient operations. Effective human interaction with the visualization supports coverage analysis, command, and control. An essential element is complexity management of the data volume, variety, velocity, value, and veracity [32] which support space-air-ground big data [33].

The paper is as follows. Section 2 highlights methods of DDDAS. Section 3 discusses multidomain results from DDDAS methods. Section 4 provides a multidomain concept bringing together space communications, avionics fly-by-feel, ground visualization, and spectrum management. Section 5 provides conclusions and future directions.

2. DYNAMIC DATA DRIVEN APPLICATIONS SYSTEMS (DDDAS)

Consider high winds affecting an avionics platform. A weather environment model of the wind can be constructed from space, air and ground sensors, but this has limited predictive value without knowledge of initial conditions, boundary conditions, inputs, parameters, and states (such as velocities and accelerations). In order to make predictions, data is needed to estimate unknown quantities. Although the wind patterns can be imaged at low resolution by a satellite, measurements by ground sensors with higher resolution are expensive and limited in range, and therefore the high-dimensional elements of the wind makes it impossible to obtain detailed measurements over a large area.

In a scenario of this type, it may be possible to use the model to guide and reconfigure the sensors so that the information content of the data is enhanced for the ultimate objective of predicting the path and intensity of the wind. One example is the ProgrammIng Language for spatiO-Temporal data Streaming (PILOTS)[1] that uses pitot tubes and other sensors to

[1] Available in open-source form at: http://wcl.cs.rpi.edu/pilots/.

determine the wind as shown in Figure 4 [34]. At the same time, the data collected by the sensors enhances the accuracy of the model by providing estimates of initial conditions, boundary conditions, inputs, parameters, and states. The integration of on-line data with the off-line model creates a positive feedback loop, where the model judiciously guides the sensor selection, sensor data collection, from which the sensor data improves the accuracy of the model. In the fly-by-feel DDDAS approach [35], the structures of the aircraft can provide real-time measurements to adjust the flight control, which is highlighted in Figure 5.

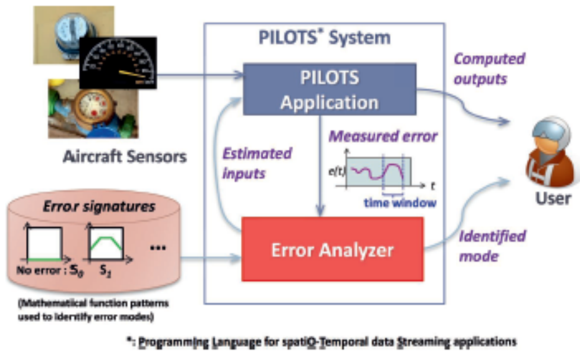


Figure 4 – DDDAS Pilots Architecture [34]

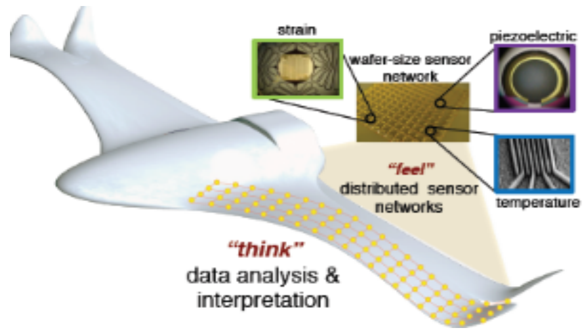
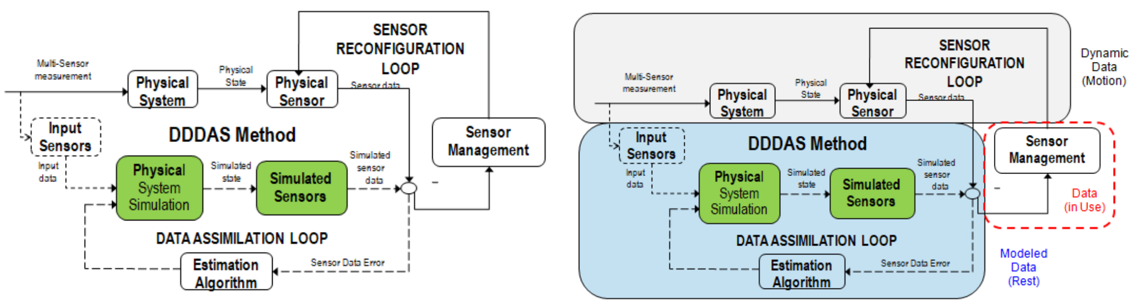


Figure 5 – Fly-by-Feel Avionics System [35]

The wind example illustrates the essence of Dynamic Data-Driven Application Systems (DDDAS). DDDAS is a conceptual framework that synergistically combines models and data in order to facilitate the analysis and prediction of physical phenomena. In a broader context, DDDAS is a variation of adaptive state estimation that uses a ***sensor reconfiguration loop*** as shown in Figure 6(a). This loop seeks to reconfigure the sensors in order to enhance the information content of the measurements. The sensor reconfiguration is guided by the simulation of the physical process. Consequently, the sensor reconfiguration is ***dynamic***, and the overall process is ***data driven***.



(a) (b)

Figure 6 – Dynamic Data-Driven Application Systems (DDDAS) feedback loop.

The core of DDDAS is the ***data assimilation loop***, which uses sensor data error to drive the physical system simulation so that the trajectory of the simulation more closely follows the trajectory of the physical system. The data assimilation loop uses input data if input sensors are available. The innovative feature of DDDAS is the additional ***sensor reconfiguration loop***, which guides the physical sensors in order to enhance the information content of the collected data. The data assimilation and sensor reconfiguration feedback loops are ***computational*** rather than physical feedback loops. The simulation guides the sensor reconfiguration and the collected data, and in turn, improves the accuracy of the physical system simulation. This "meta" positive feedback loop is the essence of DDDAS.

Key aspects of DDDAS include the algorithmic and statistical methods that incorporate the measurement data with that of the high-fidelity modeling and simulation. Figure 6(b) shows that the "data in motion" is the estimation of the sensor reconfiguration loop, and "data at rest" is the simulated data; while the "data in use" is the current simulated model data necessary to support real-time control.

2.1 State Estimation and Data Assimilation

The goal of ***state estimation*** is to combine models with data in order to estimate model states that are not directly measured. State estimation is a foundational area of research in systems and control. Relevant techniques date from the 1960's in the form of the Kalman filter and the Luenberger observer. An observer is a model that emulates the dynamics of a physical system and is driven by sensor data in order to approximate unmeasured states. The Kalman filter is a stochastically optimal observer that estimates unmeasured states. In large-scale physics applications, such as applications involving structures or fluids, state estimation is called ***data assimilation***.

The Kalman filter was developed for linear systems. However, most real applications involve nonlinear dynamics, and the development of observers and filters for nonlinear systems is a challenging problem that remains largely unsolved. Numerous techniques, which can be described as suboptimal, ad hoc, application-based, or approximate, have been developed, and many of these methods are widely used. These techniques include the extended Kalman filter (KF) [36], ensemble Kalman filter (EKF) [37], ensemble adjustment Kalman filter (EnAKF) [38], information filter [39], unscented Kalman filter (UKF) [40, 41], stochastic integration filter (SIF) [42], and particle filters (PF) [43].

2.2 DDDAS and Adaptive State Estimation

State estimation algorithms are based on prior information about the physical system. The information typically includes a model of the physical system as well as knowledge of the initial state, inputs (such as disturbances), and sensor noise [44]. Likewise, stochastic representation, for example, as a statistical description of the disturbances and sensor noise, is one method to process the information. An adaptive state estimation algorithm may attempt to learn and update the information, states, and parameters online [45].

DDDAS uses adaptation in a different sense. In particular, DDDAS seeks to reconfigure the sensors during operation. Sensor reconfiguration, driven by the model, enhances the information content of the measurements. Together, the integration of the data assimilation loop and the sensor reconfiguration loop are central to methods using DDDAS.

2.3 DDDAS for Feedback Control

DDDAS uses computational feedback, but not physical feedback. As Figure 6 shows, state estimation is a ***feedback process***, where the sensor error corrects the simulation of the physical system. The data assimilation feedback loop is implemented in computation, and thus has no effect on the physical system.

DDDAS employs an additional feedback loop by reconfiguring the sensors based on the sensor error data. The sensor reconfiguration feedback loop is also computational, and thus does not affect the response of the physical system. In contrast, feedback control uses physical inputs (such as forces and moments) in order to affect the behavior of a physical system, such as an aircraft autopilot that drives the control surfaces and modifies the aircraft trajectory. Consequently, DDDAS employs two computational feedback loops, *but does not use only use physical feedback control*. The power of DDDAS is to use simulated data from a high-dimensional model to augment measurement systems for systems design to leverage statistical methods, simulation, and computation architectures.

2.4 DDDAS Methods

The DDDAS framework, as it name implies, has been applied to many applications where modeling and data collection are utilized in engineering and scientific analysis. Hence, four attributes of DDDAS include: (1) instrumentation methods, (2) real-world applications, (3) modeling and simulation, and (4) systems software. Instrumentation methods include multidomain components in real-world situations such as space sensors monitoring the atmosphere; avionics sensors detected the air movements, computer vision detecting vehicles on a terrain road network [46], as well as, water properties in the ocean. The coordination of high-end with real-time computing requires new hardware and software approaches in the fields of optimization, data flow, and architectures to being together modeling and instrumentation methods for real world applications.

The key developments of the integration of the instrumentation, models, and software to enable the development of DDDAS include: *theory, algorithms, and computation*. The theory includes mathematical advances (e.g., retrospective cost modeling); while the algorithms support new methods (e.g., ensemble Kalman filter, Particle filter, optimization techniques). The computational considerations align with the developments in the continuing networked society such as non-convex optimization, data flow architectures, and systems design.

3. MULTIDOMAIN DDDAS EXAMPLES

DDDAS methods include many results for multidomain assessment as shown in Figure 7. From the recent *Handbook on Dynamic Data Driven Applications Systems* [23], multi-domain examples demonstrate techniques to incorporate physics models in support of domain specific operations. The three methods of measurement, context, and cyber aware methods support a combined systems aware analysis. The measurement aware techniques include air, fluid, and structural analysis [47]. The multidomain context aware methods include target tracking, pattern classification, and coordinated control as components of information fusion as applied to video tracking [48, 49, 50, 51, 52] and wide area motion imagery [53, 54, 55]. To assess the processing, cyber aware methods include security, power, and scene (data) modeling of the system. These functions operate over the layered domain operations as DDDAS-based resilient cyber battle management services [56, 57, 58].

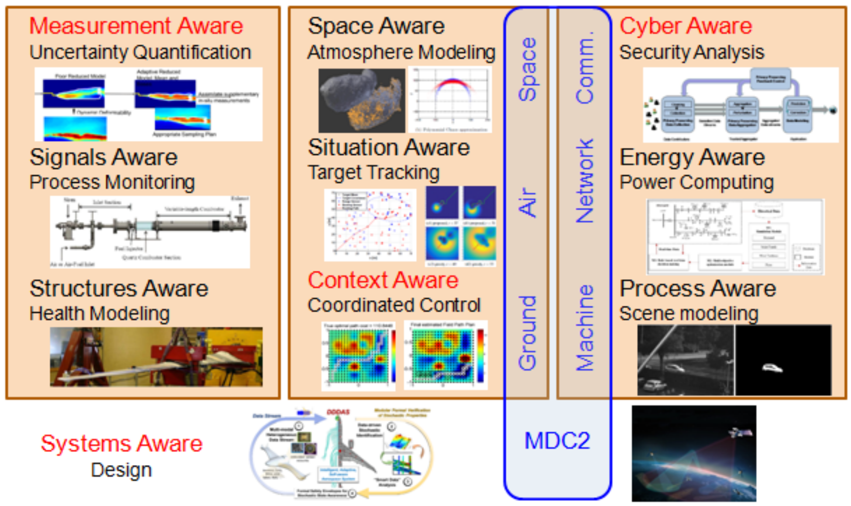


Figure 7 – DDDAS methods for multidomain command and control (MDC2).

4. MULTIDOMAIN EXAMPLE

The interest in multidomain operations requires the coordination among different platforms in space, air, ground, and cyber domains. The space domain provides valuable functions for navigation, communication, and data routing – all services for data in motion. Likewise, the modeling capabilities of predicted weather in the different domains can support the real time operations from the various data at rest. The intersection of the information is data in use. A unique scenario that leverages the many developments in DDDAS is the fly-by-feel concept for future UAVs (or a swarm of UAVs). To enable such a concept, the structural health data from the on-board sensors would need to be combined with data from off-line sources as shown in Figure 8.

The areas to support the techniques include:

Data at Rest: Provide *structure (i.e., translations)* between data for integration, analysis, and storage;

Data in Collect: Leverage the *power of modeling* from which data is analyzed for information, delivered as knowledge, and supports prediction of data needs;

Data in Transit: Develop a *Data as a Service (DaaS)* architecture that incorporates contextual information, metadata, and information registration to support the systems-of-systems design;

Data in Motion: Utilize *feedback control loops* to dynamically adapt to changing priorities, timescales, and mission scenarios; and,

Data in Use: Afford context-based *human-machine interactions* based on dynamic mission priorities, information needs, and resource availability.

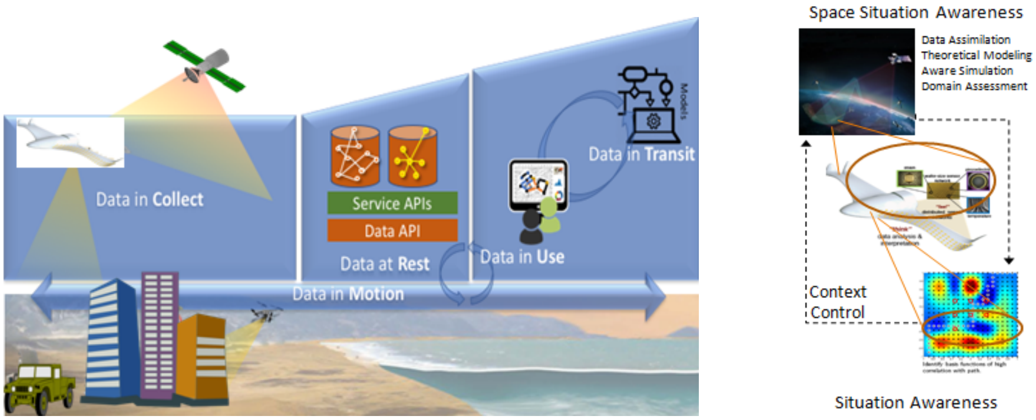


Figure 8 – Multidomain Coordination for Fly-by-Feel Avionics.

4.1 Space Domain

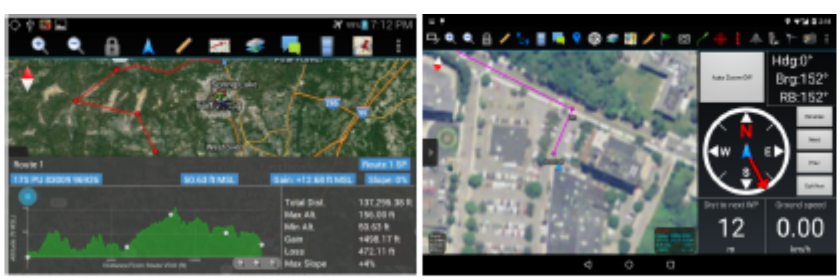
Space weather detection is important for the continuous satellite operations for space situation awareness [59]. Knowing the space weather can help mitigate the effects of threats to satellites supporting tracking, communication, navigation, and remote sensing [60, 61]. Current DDDAS efforts focus on the results of weather effecting reliable communications [62, 63, 64]. Satellite health monitoring (SHM) includes the power and electronics to control the satellite [65, 66]. Secure uplink and downlink services can provide data in use [67, 68]. Examples could be steering and processing the raw data before sending the information to the ground and Satellite Communication (SATCOM) Network survivability oriented Markov games (NSOMG) to process data on the satellite for effective digital transmission [69]. The space domain is critical for multidomain services such as the control and positing of a UAV that provides situation awareness.

4.2 Air Domain

The air domain includes the coordinated autonomous actions of information fusion and control diffusion (e.g., data in collect) such as a network of swarm UAVs [70, 71, 72, 73]. A recent example is fly-by-feel that incorporates active sensing for flying [74]. To enable such a concept, various sensors need to be designed [75] to leverage the other domains such as that of biological systems [76]. Aeroelastic sensing [77, 78], is evident as a DDDAS method to enhance real time management and control. The fly-by-feel techniques incorporate stochastic sensing and filtering as part of the on-line structural health of the aircraft that is incorporated with the measurements of position and air fluid flow [79, 80].

4.3 Ground Domain

The Android Team Awareness Kit (ATAK) [81] is a situation awareness tools that includes many feature displays for a portable device that supports multi-domain operations. While ATAK features the display of various data sources, for multidomain operations; it could provide additional information to the user towards the health of the systems for command and control [82].



(a) Route Planning tools (b) Route Navigation Tools

Figure 9 – Android Team Awareness Kit (ATAK) visualizations for planning [81].

The DDDAS rendering options support the design of a *User Defined Operating Picture* (UDOP) [83] that can be displayed on the ATAK system. The ability to plot tracks, discussions, and labels of objects [84, 85] enhances the situation understanding [86, 87]. The display could also provide feedback support to support resource management of the sensors onboard [88, 89], and determine the coordinated control and performance of the multidomain sensing system [90]. If the UAVs supported multiple imagery sensors, methods for image fusion [91] could be applied, uncertainty assessment of the incoming data [92], and methods to broker compression ratios of the data in collect and transit [93]. With the display of information, future methods could provide active support to spectrum management.

4.4 Spectrum Management

Along with the satellite health monitoring, recent efforts have focused on dynamic spectrum access (DSA) for space. Resolving uncertainties of satellite locations, data requirements, and antenna processing are needed to optimize performance. Examples include spectrum awareness [94, 95], waveform selection [96], and reasoning engines to enhance multidomain performance. Over the many aspects of the satellite performance, a reasoning strategy using a Bayes' network [97], or other reasoning engines, can be used to process the large amounts of data to robustly optimize performance. Finally, in the presence of adversarial conditions, the system provides secure communication [98], interference mitigation [99], and cyber protection [100]. There has also been recent focus on the utilization of DSA techniques for UAV networks in which the UAVs perform various sensing and transmission tasks using spectrum leased from terrestrial networks in exchange for providing relaying services for the terrestrial network [101].

4.5 System Design for multidomain management

The design of a multidomain system would coordinate the space, air, ground, and cyber domains with a user interface through the ATAK system as shown in Figure 10. The system determines the mission needs for autonomous surveillance of a designated area which gathers information from space (e.g., GPS), air (e.g., aircraft measurements), and ground Automatic dependent surveillance—broadcast (e.g., ADS-B) which is currently being researched and implemented.

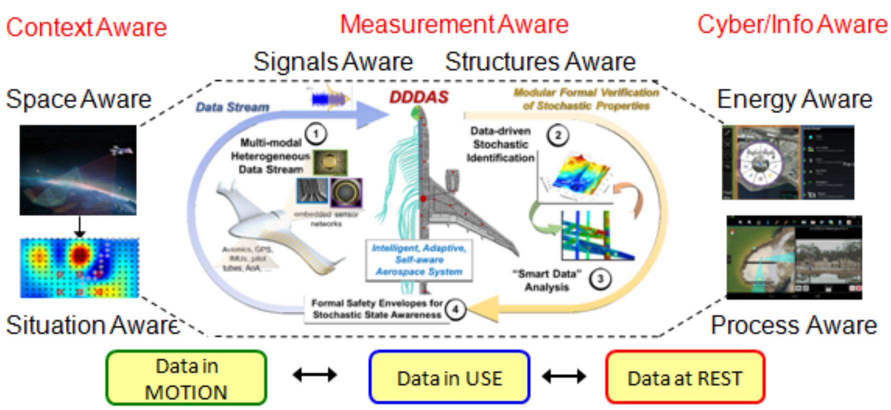


Figure 10 – Multidomain Fly-by-Feel concept

5. CONCLUSIONS

In this paper, we reviewed Dynamic Data Driven Applications Systems (DDDAS) methods for use in a multidomain fly-by-feel air platform concept. DDDAS advances support object tracking, characterization, cyber network protection, sensing, and information management. These functions typically include correspondence with ground support such as providing sensor control, visualizations, and awareness. The design leverages modeling (data at rest), real-time control (data in motion) and analytics (data in use) for multidomain coordination. Future efforts include further simulation and development towards a prototype for multidomain command and control.

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