Invited Paper

Networked Control Systems and their Applications to Smart Satellites: A Survey

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ABSTRACT

The advancement of Earth observation satellite research in past decades has demonstrated itself to be productive and increasingly important. Utilized for applications such as climate monitoring, communication, GPS, defense, and space research, our dependence on reliable satellite systems is ever-increasing. The success of satellites in these scenarios is fundamentally the result of its attitude determination system, consisting of control and estimation subsystems, which govern its sensors and actuators. For simple missions, attitude pose determination can be computed onboard the satellite. Typically, however, ground stations or other satellites (i.e. constellations) are involved in a satellite's operation, processing large amounts of data or complex control algorithms. This information and control cycle is enabled through the application of Networked Control Systems (NCS). The NCS uses a wireless network or communication system as the intermediate line of communication between plant, actuators, sensors, and other systems. This enables relatively fast communication and data transmittance over long distances, as well as the decentralization of navigation and control through system distribution. However, this method is vulnerable to various forms of time delay and packet loss, which ultimately affects the control performance of a satellite. It is demonstrated in literature that the effects of these NCS properties can be mitigated, increasing its viability, through various implementations of smart systems into the satellite framework. Using techniques such as neural networks and reinforcement learning, the satellite can perceive and act based on environmental information, while considering experiential memory and attention allocation. The following comprehensive survey discusses methods for improving the robustness of networked satellite systems from a smart systems perspective, providing an advanced foundation for these concepts.

Keywords: cognitive dynamic systems, attitude control, reinforcement learning, neural networks, smart systems, control theory, networked control systems, satellite

1. INTRODUCTION

For aerial vehicles, there are a multitude of engineering problems that must be consistently assessed for their functional and safe operation. Although structural stability and flight dynamics are crucial, the fundamental requirement for attitude control and estimation is undeniable. The attitude determination and control system (ADCS) is applicable to a multitude of vehicles, mainly unmanned aerial vehicles (UAVs), commercial airliners, submersible marine vehicles, and spacecraft. Where attitude in this context is the orientation of a vehicle with respect to some measurable reference, the ADCS enables accurate control authority over the attitude, for both autonomous and manually operated vehicles. A fairly common example of this is the assistive aspects of autopilot in airplanes for disturbance rejection.

The ADCS is the intricate union of sensors for determination, actuators for control, and algorithmic software, where without such a system, autonomous vehicle operation and precision pointing would be unattainable. Innovations in space exploration have benefited human society since the deployment of the first satellite several decades ago. Demonstrating extraordinary utility in the areas of science, engineering, and everyday life, satellites are widely used for communication, navigation, defense, and research applications. The most commonly applied satellite for these cases is the Earth-observing satellite (EOS). Implementing a robust ADCS into a satellite is vital for the success of these applications.

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Sensors and Systems for Space Applications XVII, edited by Genshe Chen, Khanh D. Pham, Proc. of SPIE Vol. 13062, 130620K · © 2024 SPIE
0277-786X · doi: 10.1117/12.3013314

For operating multiple systems simultaneously, it is often preferred to maintain control through some sort of network. These types of systems can exist in several different frameworks, such as centralized, decentralized, or distributed systems, which all have the control processor connected to the plant, sensors, and actuators through such networks. These types of systems can exist as an assembly line with multiple robotic stations, UAV clusters, or some other system with multiple operating agents. Networked systems can be desirable in long range applications, collaborative systems, or in cases where there is heavy computation and it is not feasible to have processors installed locally. However, whether the intermediate network of the control loop is a serial bus or a wireless network, there are additional considerations that must be made when designing the system, due to network-induced errors.[1,2]

The types of network-induced errors that can occur usually exist in the form of time delays and packet loss, but security and network stochasticity is also a significant issue.[2] To compensate for this, engineers have the option to improve the quality of their network, or improve the performance of their controller. A networked control system (NCS) is a controller that does the latter, being able to improve the system's robustness to communication faults. The NCS has been demonstrated in literature to perform very well when facing these issues, though they are typically designed to accommodate for certain issues at a time. The process of designing an NCS is dual, where the control scheme must be adaptive or robust as well as stable, and the network must exhibit suitable quality. If network quality is not improvable for the distributed system, then routing techniques can also be developed.[3,4]

Research in NCS became increasingly popular in the 1990's and early 2000's following the exploration of time-delayed control and distributed systems[5] in preceding decades. Surveys providing high-level overviews for this sub-field of control systems are numerous.[1–4,6–11] In 2006, T. Yang[6] provided a more comprehensive review of NCS methods in a variety of applications such as automobiles, aircraft, HVAC, and power systems, from both control and communication network enhancement perspectives. Gupta and Chow[7] introduced discussions on fault-tolerant control (FTC) applications of NCS in network security, in addition to the topics surveyed by Huo *et al.* and T. Yang.[3,6] X. Zhang *et al.*[2] discuss security control applications of NCS, presenting the problem and a significant number of solutions published for data available attacks (or denial of service, DoS), and data integrity attacks. Zhang *et al.*[9] focused on different network-induced fault modeling approaches to NCS, including signal sampling and quantization, communication delay, packet dropouts, medium access and power constraints, and channel fading. Li and Chen[10] additionally considers uncertainties/disturbances, sensor/actuator faults, network security, dynamical topology, and scheduling protocols. It was concluded by both authors that NCS should be explored in the application of utilizing non-conventional controllers for solving complex problems.

To improve the performance of autonomous systems, it has become more common in recent years to implement intelligent frameworks to various subsystems. In applying concepts such as neural networks or genetic algorithms, performance can be significantly improved in areas such as control or communication. For such a situation, a system can be known as a smart system. There are many ways of defining smart systems; one is through a system's acquisition of perception, knowledge, control, communication, and security. The application of smart systems becomes increasingly prevalent as system requirements and complexities are generally increasing. In deep space missions where communication with the Earth is not feasible, smart systems are being leveraged for autonomous actions in rovers or spacecraft.[12–15] In NCS, smart systems have been applied for fault detection, increasing their robustness towards network-induced faults, and enabling automatic route switching in networks if a node fails.[16–18] Their application towards NCS is less common in the control portion compared to the communication portion.

The purpose of this literature review is to identify overlaps between smart systems applications of NCS and satellite attitude control. It will be observed through a comprehensive review that this specifically refers to the attitude control of numerous satellites simultaneously, known as formations or distributed satellite systems (DSS). The survey is outlined in the following manner, starting with Section 2, which will overview and analyze the NCS framework, and discuss its advancements in the past five years. Section 3 will examine NCS applications of satellites and Section 4 will provide the same analysis for those applications that also implement some sort of smart system feature into their control and communication system. Section 5 will summarize the paper and propose future avenues of research based on the findings, as well as identifying observed gaps in literature.

2. NETWORKED CONTROL SYSTEMS

2.1 Introduction

The concept of the NCS had one of its first references in a multi-part 1988 publication from Y. Halevi and A. Ray,[19,20] where an analysis and design of integrated communication and control systems (ICCS) was performed. Halevi and Ray consider control systems with network mediums between controller and plant, and sensor to controller as systems with time-varying delays in discrete-time. Examined for resolving issues in aircraft, spacecraft, and process control applications, the authors note the derivation can be modified considering random delays.[19] From then on, the field has emerged to implement numerous advanced control and communication strategies for NCSs, involving different systems, with applications to network- and security-based challenges.

Self- and event-triggered control (STC, ETC)[21,22] was extensively surveyed, where the aperiodic scheme is used for computing corrective control signals under some triggering condition. The triggering condition in this context can be packet loss or delay from congested networks.[21] ETC and STC are fundamentally different. ETC continuously monitors the system and reacts to current information. In contrast, STC computes current control signals, as well as future states and control values, being proactive in nature.[21] This method is additive to other control schemes for robustness in NCS settings (i.e., PID, LQG), limiting signal congestion in these systems as an effective attentional mechanism. Qiu *et al.* provided reviewed fuzzy-model-based NCSs,[23] and sliding mode control (SMC) is explored in.[24,25] Control-through-network applications in NCS consider different models and challenges, including delays, quantization, scheduling, cyber attacks, and several more. Wang *et al.*[26] presents many modern methods of dealing with these complex systems, such as adaptive dynamic programming (ADP).

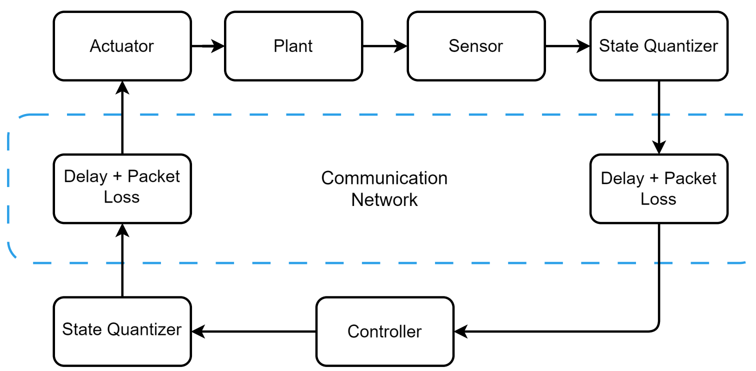


Figure 1: Diagram of Simple Networked Control System Configuration

2.2 Framework

An NCS is fundamentally different from a standard control system structure due to its intermediate communication network between components. In the standard configuration, the control and feedback signals are directly exchanged between plant and controller[11] via some wiring or physical interaction. The network layer between these same components in the NCS can utilize several different strategies, mainly separated by wired and wireless network configurations.[27] In wired networks, also referred to as digital communication networks, the components of the NCS (i.e. sensors, actuators, etc.) can be connected to the network as nodes, making industrial systems easily serviceable and diagnosable.[28] Examples of such networks are fieldbuses (HART, Profibus, Devicenet, etc.[28,29]), or ethernet.[30,31] Alternatively, in wireless networks (when implemented known as WNCS), components of NCS are connected with wireless networks,[27,32] or through some hybrid, including Bluetooth, ZigBee, and Wireless Local Area Network (WLAN).[33]

When utilizing a network as part of the control system, it is ideal to design the system to incorporate two fundamental qualities: control-of-network and control-through-network.[34] Considering control-of-network, this aspect is concerned with maintaining the quality of a network and communication, through regulating conjunction, routing algorithms, communication protocols, etc.[34] More relevant to this survey, control-through-network considers maintaining the quality of the system through control or similar performance-based routines. The impact that this characteristic has on a networked system's performance is commonly divided as Quality of Service and Quality of Control/Performance[3,34,35] (QoS and QoC/QoP, respectively). QoS deals with the measurement of communication quality in a network, such as delay and packet loss, whereas QoC follows traditional control measures, like stability, state error, etc.[34] To re-iterate, the co-design of preserving both QoS and QoC, and the authority we have over the network used is vital to the success of an NCS.

Figure 1 provides a simplified version of the NCS for a single controller applied to a plant. Here, the intermediate network (wired or wireless) is visualized. This system can also be modified to incorporate n controllers and/or n plants, which are categorized by different structures.

2.3 Categorization of NCS

There are numerous approaches to modeling and controlling systems based on the network characteristics and losses considered, as extensively demonstrated in.[10,36] Besides these aspects, we can categorize the NCS based on its structure, of which there are three:[8,11,34] centralized, decentralized, and distributed. Quasi-decentralized systems are also implemented,[6] or other hierarchical structures,[37] but the foremost three will be focused on.

2.3.1 Centralized NCS

The centralized topology, presented in Figure 2a, comprises a system of several plants, sensors, and actuators, that act independently, governed by a single controller. The controller (also referred to as the central processing unit (CPU)), executes the fusion processes, while collecting and correlating the delivered information from all other plants/inputs.[37] The centralized configuration is significantly different compared to the other two principal topologies in this way, which have no central data fusion node and knowledge is not global.[38]

Generally, excluding the intrinsic errors of real networks, utilizing this configuration is theoretically optimal and beneficial in this respect.[8,37] Not without its limitations, however, the centralized configuration consistently suffers from the high amounts of data available for the CPU to continuously process. This computational burden puts the CPU at risk of failure, potentially resulting in a complete system failure.[8] Because of the application of a single high traffic control node, the available bandwidth also becomes a significant issue, as well as the cost, computation time, and resultant delay. For larger control networks (such as urban traffic or manufacturing plant applications), these effects are pronounced as the result of its poor scalability.[8,39,40] As such, decentralized configurations are explored to surpass these issues.

2.3.2 Decentralized NCS

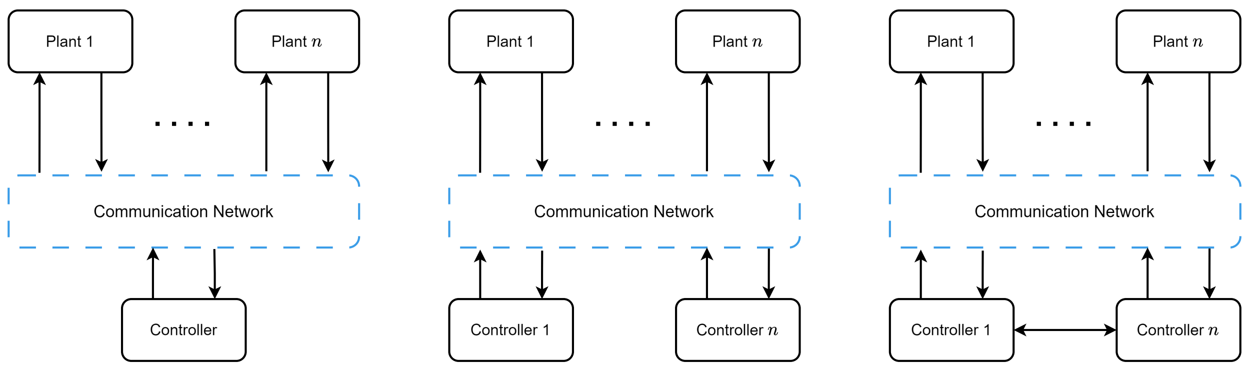
For the decentralized topology, instead of utilizing a single processing node for control, each plant and associated sensor/actuator nodes are coupled with a dedicated control node, as presented in Figure 2b. The modeling of these systems can therefore be treated as an NCS (single-node basic structure) with multiple feedback loops, as described by Ge *et al.*[8] and extensively implemented by Andersson *et al.*[41] Since computation is local and control nodes coupled to plants across the network do not communicate with one another,[8,34] the data fusion is also performed locally and autonomously by each control node.[37]

Applying the decentralized configuration, most of the downfalls of the centralized system are bypassed. Since a local plant's control actions are computed by its local controller, the system complexity and computational burden is significantly reduced.[8] Issues of bandwidth and time delay are also reduced by association. Though decentralized control is cited as being more suitable for largely scaled applications compared to the centralized alternative, scalability issues are however present. Decentralized control systems can still operate to achieve a global goal, but since there is no communication between control nodes, there exists an absence of information,[8,34] resulting in sub-optimal control performance. At larger scales, this manifests into performance deterioration.

2.3.3 Distributed NCS

For larger systems, such as internet of things (IoT) and wireless network applications, the distributed system architecture is more commonly applied. Depicted in Figure 2c, the distributed topology takes the same form as the decentralized topology, where dedicated control nodes are paired with their associated plant. The exception is that the control nodes are able to exchange information between neighboring controllers.[11] The distributed NCS is described in literature to have two fundamental characteristics:[8,11,34] the system goal at the global level is achieved by the plant being characterized by numerous distributed simple subsystems, and a shared communication network is utilized to share information globally.

By having information shared between control nodes, the NCS can better understand plant dynamics and cooperate to achieve the defined goal. The bidirectional flow of information is a significant factor towards a distributed system's robustness,[34] as well as an indicator for an intelligent system. Additionally, because of their dedicated control nodes, the distributed and decentralized frameworks ultimately benefit from modularity. This aspect is beneficial from an engineering scope, as it minimizes the amount of re-design that needs to be performed across multiple design iterations.[42] Significantly improved scalability[34] is another property of the distributed framework, overcoming the sub-optimality of the decentralized system, and the vulnerability to network imperfections and limited processing of the centralized system.



(a) Centralized NCS (b) Decentralized NCS (c) Distributed NCS

Figure 2: NCS Topologies

2.4 Challenges of NCS

As previously discussed, the NCS is fundamentally different from the standard control system framework. In most configurations, this means an intermediate communication network (wired or wireless) between the controller and the plant input and output. The input and output lines are typically populated by signal converters (digital-to-analog (DAC) or analog-to-digital (ADC)), sensors, and actuators. With the network between these major nodes, information can become altered in many ways, affecting the overall quality of system performance. Implementing NCS systems generally improves the serviceability and diagnosability of a system, as well as makes distributed systems significantly more feasible than point-to-point connections in traditional control configurations.[36] However, its weaknesses must also be considered in the design of these systems. The many limitations involved in implementing an NCS framework into a system are well defined in literature.[8,11,36] Examples of which are presented as the following subsections.

2.4.1 Time Delays

It is well known that time delays (especially those that are large compared to sampling interval) within the control loop can result in performance deterioration. This is typically a computational issue in traditional digital controls. For the NCS, there are several types of time delays that can occur, typically manifesting themselves as computational or transmission delays.[8] The occurrence of packet loss could also be considered an additional type of access delay. Computational delays exist in sensors, actuators, controllers, and any other intermediate node in the control loop. The speed of the hardware is a contributing factor, as well as the volume of data that is being transmitted across the channel for processing. In transmission delays, the communication network is the cause. The network can exhibit delayed behaviour due to the quality of the network and the amount of data being transmitted or bandwidth available.[8] The transmission and computational delays are similar in scope, but the medium in which they occur is different. Transmission delays can be further categorized by the statistics of occurrence (deterministic or random) or the delay duration type (constant or time-varying).[8]

2.4.2 Packet Loss

When information transmitted over a network is not received successfully, this is generally considered the result of network-induced packet loss. The occurrence of packet loss can usually be attributed to poor network quality or congestion,[11,36] and can be modeled to be deterministic or random processes (such as Bernoulli or Markov processes). The effect of this type of network induced error is similar to that of the delay, where information is not current and there is subsequent controller breakdown, but for packet loss the incident is especially harmful, as the NCS becomes an open-loop system at these instants.[36] Since packet loss is based on the quality of the network and not control scheme or hardware, it is not considered controllable, and robust network protocols (such as TCP/IP) must be implemented.[36] Modern endeavors are involved in integrating packet loss robustness with the control law, instead of the network protocol solely, as demonstrated in.[43–45] In relation to time delays and packet loss, another network error is jitter, which is signal distortion caused by poor synchronization.[11]

2.4.3 Security

More recently, the cybersecurity consideration of NCS has been considered by a growing number of researchers. Since networks (especially wireless networks) are generally prone to interception.[11] Denial of service (DoS) or deception attacks are typically the most common when applied to NCS,[11,46] where the former involves jamming the network to prevent signal routing between nodes, and the latter intercepts information and replaces it with false data. The research conducted by Gautam *et al.*[11] and Pang *et al.*[46] reviews numerous occasions where these types of security breaches have been successful and detrimental, as well as preventative methods in networks and control systems.

2.4.4 Channel Fading

In network channels (especially in wireless channels), signal attenuation, disturbances, distortion, and packet loss can cause a phenomenon known as channel fading.[8,47] Channel fading in multipath communication is when signal fluctuations occur as a result of these network disturbances, and ultimately, information is lost or its quality is corrupted. Minor disturbances of identical signals bound for the same destination can result in fading in the form of destructive or constructive interference, where superposition is expected.

2.4.5 Quantization

For the simplification of simulations, it is commonly assumed in literature and theory that the data between the controller and actuator/sensor is perfectly preserved in terms of its precision. However, in real applications, measurement equipment and DACs/ADCs do not have arbitrarily large output precision, and the signals are quantized.[36] Quantization processes are often involved in data rounding and truncation, and are an issue in traditional digital control systems as well as NCS. In the NCS, the communication network is the medium responsible for quantization.

2.4.6 Sampling Interval Decision

In NCS, the decision of the sampling interval is important for ensuring information is transmitted and received across the communication network effectively. This is an issue for traditional digital control systems as well, such as when considering hardware limitations, but in NCS this is important to mitigate issues arising in high traffic systems. The discussion of bandwidth and its relationship to system performance has been discussed previously. For small sampling periods, a large amount of data is being generated and the system will likely congest, resulting in packet loss, delays, etc.[11] For larger sampling periods, however, although the traffic is light through the network and low frequencies are sometimes ideal for control law computation, excessively large sampling periods can still result in instability. Choosing the sampling interval in an NCS is an optimization problem between system performance and network congestion. Techniques of time- and event-triggered systems have been extensively explored to reduce network congestion for these purposes.[11]

2.5 Advancements in NCS

2.5.1 Observations on Modern NCS

Since the challenges discussed in Section 2.4 have posed an issue in NCS implementation for real-time systems since their conception, there is a considerable number of solutions that have been researched. These solutions consider one or several of these issues, in systems with a variety of topologies and for different applications. This section aims to address these control advancements in recent years. Advancements on improving network routing and quality are not considered in a general scope, but will be examined further considering intelligent aspects in Section 4. Table 1 categorizes these approaches based on the challenge, where it can be observed that an extensive amount of research has been conducted on NCS techniques in the past five years. Generally, most methods are directed towards time delay and packet loss compensation in the control loop, where research into secure NCS is increasing. There are very few recent publications on sampling rate selection for optimal NCS operation, where most are from over a decade ago,[48–50] also having to do with packet loss and time delay compensation. The majority of these methods are directed towards multiple network-induced challenges instead of a single one.

Table 1: Recent Control Advancements to NCS Challenges

Network Challenge	Control Method	Reference
Time Delay	Event-Triggered	51–53
	Adaptive SMC	54, 55
	Robust	56–58
	Fuzzy Systems	53, 59
	Neural Network	60
	Model Predictive	61, 62
	Cognitive	51, 63–68
Packet Loss	Event-Triggered	69, 70
	Adaptive SMC	54
	Robust	43, 56, 58
	Fuzzy Systems	71–73
	Model Predictive	44, 45, 62, 74, 75
	Cognitive	63–68
Security	Event-Triggered	51, 52, 76–79
	Robust	80
	Fuzzy Systems	78
	Model Predictive	75, 81, 82
	Cognitive	51
	Markovian Sys.	83
Channel Fading	Robust	47
	Markovian Sys.	83
	Optimal	84
Quantization	Event-Triggered	53, 69
	Adaptive SMC	55
	Robust	80
	Fuzzy Systems	53
	Model Predictive	61, 74, 85

2.5.2 Cognitive Control

From the literature surveyed thus far, it can be noted that one type of control strategy that is fairly novel as well as successful in mitigating network-induced issues is the cognitive control structure for NCS. The cognitive structure is based on the concept of a cognitive dynamic system (CDS), which is a unique take on smart systems. Based on the concept of human cognition defined by J. M Fuster in 2005,[86] S. Haykin started to postulate the structure of a cognitive dynamic system from an engineering standpoint and what it would imply. A dynamic system can be considered cognitive if, while operating in an unknown/non-stationary environment, it is capable of utilizing the perception-action cycle (PAC), memory and attentional mechanisms, inherent intelligence, and some form of communication/language.[87] Haykin describes a new concept, cognitive control, as “optimal decision making in the actuator under feedback guidance from the perceptor”.[87] From a neuroscience perspective, cognitive control involves learning and planning, and exists in the prefrontal cortex of the brain.[88] From an engineering standpoint, the framework of the cognitive control system was not yet formulated, until a paper dedicated to the topic was published by Haykin in the middle of 2012,[89] followed by[90] later that year. In 2014, the amount of literature on cognitive control increased significantly.[88, 91–93] Simply put, in a cognitive dynamic system, cognitive control minimizes the unknown information in a non-stationary environment using the perceptual and executive memories it gained from encountered situations. The framework utilized under CDS uses a unique ”two-state” model, where the novelty comes from the entropic state, which quantifies the information gap between the system and the environment. Though several examples have been provided for NCS applications, this area of smart systems is still relatively under-researched, particularly in the area of NCS applications for robotic systems, or for aerospace systems in general. Several reviews have been conducted on this topic,[94–96] highlighting potential applications across a variety of disciplines, such as internet of things (IoT) and smart grids.[97]

3. SATELLITE APPLICATIONS OF NCS

3.1 An Introduction to Spacecraft Attitude Control

For spacecraft, utilizing effective attitude determination and control techniques is absolutely vital. Where attitude is an aerospace vehicle's angular and lateral position relative to any reference, we typically prioritize achieving and maintaining authority over attitude for a wide variety of applications. In satellites specifically, we consider applications such as communication/broadcasting, GPS, climate monitoring, and defense. Accuracy is paramount to ensure effectiveness in these essential applications, and as such, the ADCS requires the coordination of sensors, actuators, and algorithms. These systems are not exclusive to space systems, and can also be applied to other aerial or submersible vehicles, such as airplanes, UAVs, and vessels for marine exploration. In the context of Earth observing satellites, we typically want to maintain high pointing accuracy in three rotational axes with respect to a target. Other spacecraft might consider lateral movement facilitated by thrusters, but this is relatively uncommon in satellites. These systems enable satellites to be able to be controlled remotely and have some degree of autonomy, which is important due to their unserviceability.

Focusing on the ADCS framework, the actuators are coupled to the attitude control decision, and the sensors enable an attitude decision to be made. Algorithms are performed for computation within these processes and to join them, forming the control loop. In attitude determination, the goal is to determine the spacecraft attitude matrix from a set of measurements determined by the sensors, such as solid state star trackers, magnetometers, and sun sensors.[98] Representing the attitude matrix from a set of measurements can mainly be performed statically or using filtering methods which utilize past knowledge of states.[98] Examples of static algorithms include the TRIAD, QUEST, or ESOQ methods. Memory based methods are typically categorized with attitude estimation and account for stochastic variation in the environment, like the various Kalman filter forms or the maximum likelihood approach.[98] In attitude control, we use the spacecraft state measured by the determination algorithm, compare this to the desired attitude, and derive a command to be sent to the actuators in order to achieve this over time. Attitude control can be done actively in this manner, but also passively, using the effects of the gravity gradient on a boom or aerodynamic effects of the atmosphere. Again, most often we consider rotational stability for pointing accuracy in observation satellites, but thrusters are also used to perform orbital maneuvers.[98] For active situations, where we want to achieve control authority in three axes or reduce the libration/spin effects of passive methods, numerous satellite actuators can be utilized. Reaction wheels (RW), magnetorquers, control moment gyros (CMG) are among the most common of these. Research on both physical and simulated manifestations of these concepts are numerous, but will not be discussed in detail for brevity.

3.2 NCS for Spacecraft

The connection between attitude control and NCS does not exist within the current Earth observing satellite and ground station configuration. A satellite utilizes four main subsystems that are essential to its operation: the power subsystem, the communication subsystem, the ADCS, and the telemetry, tracking, and command (TT&C) subsystem. In attitude determination and control, the first two systems are supplementary to the ADCS and TT&C, which are the primary systems for this application. The first component of TT&C, telemetry, is responsible for providing the ground system with satellite diagnostics, such as voltage, fuel tank pressure, RW speed, or environmental information.[99] The tracking subsystem, as part of the ground station, locates the satellite and provides elevation and azimuth angle information.[99]

For the command subsystem, the attitude and diagnostic information is received and processed, and commands can be issued to the satellite through the uplink from the ground station.[99] The commands issued are not real-time control signals for the actuator to achieve an attitude, but rather the reference signal (i.e., desired attitude), and other commands such as battery reconditioning, thruster firing, or heater switching. The control signals are computed on-board the satellite, via the ADCS. Because of the current TT&C structure in most Earth observing satellites, applying the NCS framework using the ground station as the control processor would be impractical due to the delay of relay time and small visibility windows for the ground station.

For NCS to make sense within the context of satellite attitude control, where the control signal processor is separated from plant and sensor/actuator nodes by a network, the distance between the two components would need to be considerably shorter. Currently, the packet quality and security of them from ground station to satellite is a network quality (i.e., "control-of-network") and data encryption problem, rather than a control issue. Considering NCS and current technology, the most viable application is for a satellite-to-satellite, or satellite-to-space station based control loop. Although a centralized control configuration of one or more satellites has been proposed,[100] distributed NCS frameworks for multi-satellite formation control are more actively being researched and deployed.

3.3 NCS for Distributed Satellites

In autonomous satellite formation flying, many small satellites can be deployed to replace the functionalities of a single larger, more expensive satellite.[101] The states of these satellites are dynamically coupled through a dynamic control law, and at least one must adhere to two rules to retain the definition of a formation,[101] which were defined by D. Wang *et al.* The first is that the satellite must utilize the state of another satellite as part of its tracking control law, and the second is that the satellite uses its tracking control law to track the desired signal relative to another satellite. DSS are an important application of mainly distributed NCS, where no ground station is involved and satellites with predetermined functions must maintain wireless communication with each other, for exerting commands, and sharing data and resources.[102] With DSS, the reliability and redundancy of missions can be generally improved. The cost and detriment to the mission would be significantly reduced if one of many autonomous satellites suddenly failed, compared to the failure of an individual agent. DSS can be thought of as having a longer life span as well, due to modularity.[103] Like traditional single or uncoordinated satellites, distributed formations have been successful in, and are ideal for communication, navigation, defence, rendezvous/docking missions, and efficient, simultaneous subject observation/data collection.[104] An example of a possible distributed satellite configuration is illustrated in Figure 3.

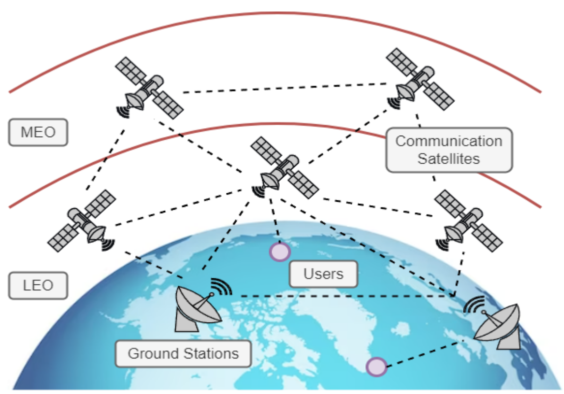


Figure 3: Example of Distributed Satellite System

Typically, DSS can be classified as either trailing formations, clusters, or constellations, and there are several examples of each that have been successfully deployed or are in progress. Trailing formations have spacecraft sharing an orbital path, where their distance is constant and pointing maneuvers are synchronized relative to each other. A recent example of this is the European Space Agency's (ESA's) PROBA-3 spacecraft pair,[105] which is planned to be deployed as a pair in 2024 for guidance, navigation, and control (GNC) strategy validation. The PROBA-3 will do so autonomously, without the aid of ground stations. Another older example of trailing formation spacecraft is NASA and the German Space Agency's (GSA's) GRACE mission. This mission performed various gravity and climate experiments, reviewed by Chen *et al.* and Frappart in,[106,107] and inspired original research from Wouters *et al*.[108] Cluster/swarm and constellation DSS are similar to each other in their high agent amount, whereas clusters fly along the same (or similar in path) orbit maintaining the distance constraint of trailing formations, and constellations operate in different obits, surveying a wider coverage but still cooperating under ground control command. They can also be differentiated simply as local and global clusters.[103] The Cluster Quartet of the ESA[109] is one such example of a small cluster, utilizing four coordinated satellites in geopolar orbit for ultra-low frequency (ULF) waves. The ESA also have achieved unprecedented accuracy in Earth's magnetic field measurement with their three satellite Swarm.[110] M. Volwerk discusses other missions involved in this research, Double Star and THEMIS, as well.[109] Distributed satellite Constellations have been proposed for many years, primarily for their global communication and Global Navigation Satellite System (GNSS) purposes, in projects such as IRNSS, Galileo, and GLONASS.[111] One prominent example of these large distributed systems is the Starlink Project from SpaceX, which has launched several thousand small satellites and plans more as it nears its second-phase mega-constellation.[112,113] It's proposed for this constellation to use an optical communication technique known as Laser Intersatellite Links (LISLs), which will enable faster data transfer, smaller and therefore lighter antennas, narrower beams, and lower power requirements.[113] The narrower beam technology allows for increased security and decreased interceptability. A survey from Bandyopadhyay *et al.* provides more examples of proposed, deployed, and in progress formation missions[114]

Besides the existing issues previously discussed involving NCS in general, DSS of all types are vulnerable to additional concerns. One issue that should be reinforced, however, is security in communications. This was especially considered in the Starlink[113] project, where vast amounts of sensitive data are hypothetically interceptable. This applies to defense and navigation distributed systems as well. Designing formation architectures and their associated disturbances is also challenging, where for example, additional and very high-performing sensors are additionally required for attitude synchronization.[103] These satellites are also subject to the same design and environmental challenges of typical satellites. In Section 3.4, solutions to satellite formation control are presented in the context of NCS. Relevant examples involving formation control, not considering errors introduced by network behaviour, in distributed space systems can be found in the following publications.[115–123]

3.4 Advancements in NCS for Satellites

For satellite formation control with NCS, the trend observed previously in Section 2 is repeated, where most publications are focused on time delay or packet loss mitigation. Nearly all applications of NCS towards satellites surveyed in this paper from the available literature were on the topic of DSS. Alternatively,[124,125] discussed maintaining control as well as security within a single bused satellite system.

Liu and Kumar were relatively early adopters of the NCS approach to distributed satellites, introducing a control scheme that was robust to network induced varying time delays.[126] The authors derived a digital controller that guarantees convergence up to a specified delay for their nonlinear system based on Hill's equations, the first of its kind at the time of publication. Soon after, X. Bai *et al.* take a model predictive control (MPC) approach to the NCS problem in formation flying to compensate for packet loss and time delays in weak wireless connections.[127] Authors demonstrated improved performance compared to a PD controller for their simulated application with two satellites, one primary and the other secondary. Zhou *et al.*[128] consider time varying delays in their research, as well as modeling uncertainties and external disturbances. Implementing a robust sliding mode estimator, their control law globally converges without the use of spacecraft velocity measurements, making it ideal for low-cost clusters. In 2015, A. Einafshar concluded their thesis on fault-tolerant control structures for satellite formations.[129] Their work compiled their research in this field, utilizing colored petri nets to achieve attitude control that is able to reconfigure its network connections in the presence of communication faults.

Publications on NCS-based DSS have been far more dense in the past five years. Kempf *et al.* explored both robustness to failure and packet loss in their 2018 formulation[130] through the dual design of NCS. With a unique communication system that enables the commanding satellite of the cluster to be a variable entity, catastrophic failure of all satellites can be avoided from the failure of the leading one. Additionally, an MPC controller was derived, able to compensate for the aforementioned network errors, as well as environmental disturbances of magnetic field and gravity gradient. Damiana also utilizes a similar networked MPC approach in their thesis, implementing further environmental errors.[131] Similar to,[128] Zhu *et al.* apply a formation structure that reduces the amount of communication in the system overall, by giving the commanding satellite authority over a small amount of satellites, which in turn have authority over several others, referred to as a "tree".[132] They apply a novel integration of graph theory and consensus algorithms for accurate formation control, as well as variable time delay compensation. MPC was also utilized by Y. Zhao and Q. Zhu in a relatively unique manner, being to counter the effects of DoS attacks.[133] A hybrid event-triggered MPC controller was implemented by Kempf *et al.* that same year, primarily with the goal of mitigating packet loss and controller failure in cooperating satellite systems.[134] Note that cooperating systems and standard primary-secondary structures previously discussed are fundamentally different, where cooperating formations all act on an equal importance. An additional entry into the popular MPC-based NCS comes from L. Cao *et al.*, where delays are accommodated in three degree-of-freedom (DOF) air bearing spacecraft simulators.[135] Pedroso and Batista[136] explore mega constellations in their research, compensating for network effects using distributed MPC methods. Both Hu and Shi,[137] and Zhao *et al.*[138] apply event-based methods to satellite formation attitude control. Their methods are proposed for reducing the use of communication resources and accommodating errors from networks, but these concepts are lightly touched on, and are referenced as being focused on in future works.

4. SMART NCS FOR DISTRIBUTED SATELLITE SYSTEMS

4.1 Introduction to Smart Systems

The integration of smart systems and NCS is the next natural step towards progress in the field. The concept of a smart system has been around for quite some time, but its definition is loosely defined. Overall, a smart system is a system that can mimic human intelligence in a general capacity or for some specific task. Akhras[139] defines the goal of achieving smart systems is to produce a non-biological system that is able to achieve the optimality of a biological system, in terms of functionality. They then go on to outline the general requirements, expectations, and prospects of these systems. Alter[140] goes further, with the goal of generally characterizing the smart system through a multidimensional viewpoint. We can also view the CDS definition (see Section 2) as a suitable definition for smart systems. A general diagram of smart systems is illustrated in Figure 4, incorporating Fuster's cognition and system interaction with a digital environment, enabling communication with a user, another system, etc.

Smart systems have gained prominence in engineering as computational technology becomes faster and more powerful, and we desire systems that can complete more complex tasks. Specifically, for space exploration, increasing the intelligence and autonomy is necessary for non-Earth orbiting missions, as relaying simple commands becomes evermore impractical. As a modern example, MDA is actively investigating the use of artificial intelligence (AI) on the newest iteration of the Canadarm. Other examples of AI being leveraged for space exploration are found in image recognition, mission planning and scheduling, and navigation and control.[12–15] Section 4.2 will survey several implementations of this concept, mainly for satellite formation attitude control.

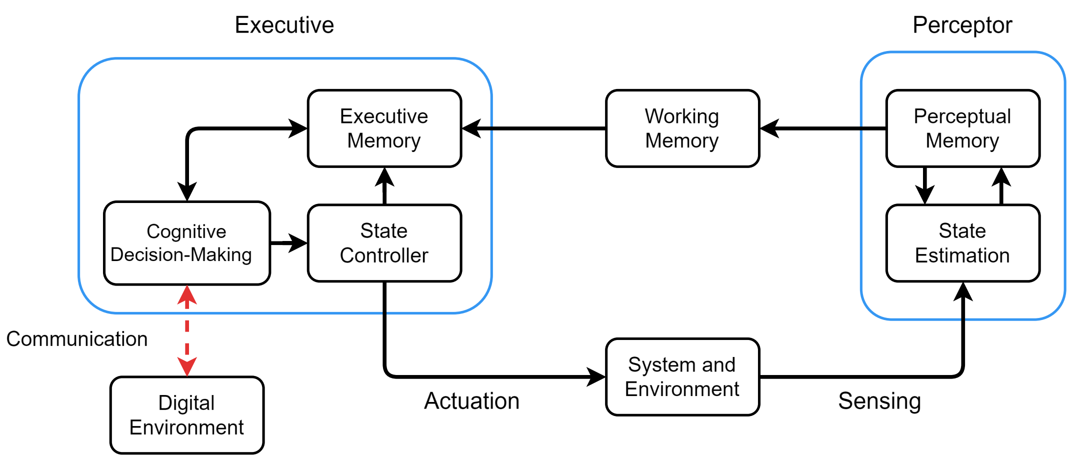


Figure 4: Smart System Framework

4.2 Advancements in Smart NCS for Satellites

Incorporating smart NCSs (SNCSs) into distributed satellite systems has been demonstrated to improve attitude control and reliability in communication. The smart approach to satellite attitude control is not new,[141–143] and comparatively more developed than its NCS counterparts. The dual design of control and network routing in these systems has increased cooperation capacity in simulations and robustness to network-induced errors. Section 4.2 will mainly discuss the intelligent control advancements for distributed satellite NCS that contribute to its classification as a smart system. These methods are part of the NCS field, so the communication robustness is increased, but the network quality is mostly unaffected from a technical or routing level. There have been many advancements in cognitive routing strategies (significantly more compared to NCS), discussed in Section 4.3.

Utilizing neural networks for their intelligent predictive control approach, Cheol Cho and Soon Lee[60] compensate for time varying delays and network stochasticity with their SNCS. Control is formulated online and the stochastic environment is predicted using a Markov chain dynamic Bayesian network. The network medium is between a single satellite and the ground station. Also aside from formation control, Dong *et al.* apply an adaptive fuzzy SMC (AFSMC) in their flexible satellite simulation to compensate for network time delays within the shared serial bus.[144] R. Liu *et al.* consider network induced time delays and external disturbances in their three satellite formation control model,[145] effectively utilizing nonsingular fast terminal sliding mode control (NFTSMC) and Chebyshev NNs. Applying a similar control structure to Liu *et al.*, Zhou *et al.* apply radial basis function (RBF) NNs and NFTSMC in their work[146] for time delay counteraction. Their application uses an additional two satellites, and the "tree" configuration of satellite command previously discussed is applied. The fuzzy systems, Chebyshev NNs, and RBF NNs were applied to approximate nonlinearities and unmodelled bounded disturbances in the system.

More recently, hybrid RBF NN and event-triggered strategies are utilized for wireless communication or general shared bus attitude control in satellites.[147,148] These methods demonstrate adaptive behavior and robustness to external disturbances, modeling errors, and communication errors due to their networked structure and unification of SMC methods. Tong *et al.* focus on accommodating delay and packet loss in general intermediate single-satellite networks as well with an iterative and predictive fuzzy clustering model.[149] Their adaptive method exhibits increased speed, and tracking accuracy and efficiency compared to the networked fuzzy SMC (NFSMC) and networked predictive output tracking control (NPOTC) algorithms it was tested against. Further examining DSS, Chen *et al.* analyze the ground control of a ten satellite formation using a robust H_∞ tracking scheme integrated with an event-triggered mechanism, and fuzzy systems to interpolate the Hamilton-Jacobi Inequality (HJI).[150] Their method proved effective, and robust against time-varying packet loss, time delays, and external errors. Event-triggered fuzzy control strategies are similarly applied by Aslam and Ma, utilizing outputs for reducing network transmissions.[151]

There is a dearth of literature involving data-driven control or more modern machine learning (ML) approaches to NCS in satellites. Previously analyzed methods featured iterative or shallow adaptive feedforward networks, not typically applied for more complex tasks. Pokhrel and Choi[152] highlight the many benefits of data-driven communications and control, including the efficiency and improved performance considering network errors. Sedghi *et al.* present open issues and advancements in ML driven NCS, though applications to spacecraft and satellites are not considered. They note the same need for expansion, where ML can significantly enhance ETC architectures. An example of cyber attack prevention within a single satellite serial bus is explored by Wu *et al.*,[153] using secure control utilizing deep reinforcement learning (DRL). Their approach uses data and offline training to establish a policy for attack protection, demonstrating stability and functionality over standard control methods that fail under such attacks. Considering attacks and other network induced errors, ML has also been explored for identifying these faults.[154]

Considering the definitions of cognitive or smart systems, we can identify that the reviewed NCS methods can be categorized as such, mimicking select mechanisms exhibited by biological systems. All systems examined make use of the PAC, making informed decisions computed by the executive based-on perceived information. The cognitive decision-making systems have been integrated with the state controller, most commonly in the form of three-layer NNs or fuzzy models. Accessible memory on multiple operation layers is absent in most these systems, except for replay memory utilized in.[153] Consideration of past information is utilized in iterative methods (e.g.,[149]), but is not considered true memory. The randomly occurring errors of an NCS necessitate the application of attentional mechanisms, which mainly exist in these systems as event-triggering strategies. ETC is known to save computational resources, initiating only when faults are detected. Intelligence is difficult to characterize, but it can be evaluated based on the relative efficiency of a smart system considering its performance, and effective unification of the other cognitive processes.[94] The examined systems exhibit some degree of intelligence, though the utilization of more defined memory mechanisms and data-driven methods would increase this. The DSSs considered in this section apply communication for functionality, where its quality is improved with NCS methods. Section 4.3 will investigate adaptive communication between systems, further encompassing the smart system definition.

4.3 Advancements in Smart Communications for Satellites

Research involving intelligent communications in DSS is comparatively more numerous than that of SNCS. Efforts towards increasing LEO distributed satellite applications by private companies such as SpaceX are growing, implying increased communication and observation. Other issues arise from this however, as satellites part of DSSs must be able to communicate with each other and Earth at large scales, where stochastic interactions and their inevitable network faults/attacks cannot be accurately accommodated for by models alone. Referring back to Figure 3, the communication links between distributed satellites, users, and stations is visualized on a small scale. It has therefore been proposed by many that AI can be leveraged to proactively and dynamically adjust communication links to address these issues, as well as integrate complex systems into current infrastructures.[155] Dynamic routing and smart communication methods that use AI will additionally integrate optimality and security within systems, increasing autonomy. To reiterate, these methods are known as "control-of-network" methods, which control the quality of the network in an NCS. Homssi *et al.*[155] and Fourati[156] provide a significant overview of this topic, surveying state-of-the-art methods.

For mega-constellations, Liu *et al.*[16] apply DRL for energy efficient routing protocols. With offline training and online learning, their method selects the next communication node to transfer to, where experience replay is utilized for parameter updates and improved decision making. Abdelsadek *et al.*[157] implement DRL for a similar a application, where the spectral efficiency of their proposed application was significantly higher than typical methods with reduced mean squared error (MSE). Mao *et al.*[158] leverage DRL for a similar application, valid for a variable number of acquisition, pointing, and tracking (APT) terminals. R. Lent[18] makes routing decisions based on spiking neural networks (SNN), whose weights are continuously updated with RL, and Liu *et al.*[159] additionally explore an alternative DRL strategy to solve and optimize random access problems. Cui *et al.*[160] incorporate a robust event-triggering strategy with their DRL based dynamic routing structure, enabling efficiency in task scheduling.

5. CLOSING REMARKS

The basic concepts of attitude control in satellites, NCSs, and smart systems were first introduced. Their respective relevance to engineering research and society is briefly discussed, along with related surveys involving NCS. The NCS as a framework was introduced and discussed in Section 2, outlining its associated categories and issues. Modern advancements in the field were evaluated and categorized as solutions. NCS applications of satellites, specifically DSS attitude control, were discussed next, illustrating the need for adaptive cooperating satellites. To further increase autonomy to accomplish complex tasks, smart system integration with DSS was explored in Section 4, on both control and communication levels.

As it can be demonstrated from literature surveyed in Sections 3 and 4, the research on smart applications of NCS towards satellites and DSS is rather minimal. Most methods surveyed focus on networked communication of single satellites and control methods are some combination of fuzzy, NN, or event-triggered methods. There are likely several research avenues in SNCS that have not been explored, such as utilizing a more diverse set of intelligent control methods, for the numerous communication and formation configurations that can be applied. There is a notable lack of data-driven or RL-based NCS specifically, where cognition would be increased with improved memory and attentional mechanisms. The application of dynamic routing as explored in Section 4.3 with SNCS is also not considered in the DSS field, where doing so would increase robustness in unstable or unsecured networks considerably. In Section 2, the concept of cognitive control and its NCS formulations of such were discussed. RL and RBF NNs are applied as an additive mechanism to nonlinear controllers and the unique CDS structure in networked robotic systems, demonstrating exceptional knowledge of the system and network stochasticity. The overlap between satellite formation attitude control and cognitive NCS (CNCS) is currently unexplored. Based on the significant results of the CNCS papers surveyed in Section 2 (and the other CDS formulations), it is reasonable to suggest that investigating this research gap would be worthwhile to the fields of DSS attitude control, smart systems, and NCS, through a novel demonstration.

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