A Systems Model for Computation, Communication, Command and Control (C4) in a Spacecraft or Satellite Cluster

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Abstract

A Computation, Communication, Command and Control (C4) model is proposed for the scenario of a space-bourn remote sensing application involving a spacecraft or satellite cluster. This paper considers the distributed processing nature of such an application together with the highly dynamic free space optical interconnection network deployed for communications. The C4 model provides for a unified and comprehensive modeling of these four aspects. An overview of the C4 model including its sub models is presented in this paper. A simulation is also briefly described.

1 Introduction

Command and control (C^2) resources and functions of spacecraft and satellites are reasonably well deployed. Command, control and communications (C^3) resources and functions, especially important for unmanned spacecraft and satellites, are receiving greater attention nowadays. Command, control, communications and computer systems (C^4S, also, C^4 noted as a synonym) integrate computer systems into this structure and are likewise of recent interest. Commercial technologies that support these types of systems are available on the market. At the same time, research and development continues on space-based networks that interconnect satellites, spacecraft and ground stations. It is clear that integrated systems are of great interest in spacecraft and satellite operations.

Typical distributed computing involves multiple processing elements usually housed in geographically dispersed cabinets interconnected by a network. Local Area Networks (LANs), Metropolitan Area Networks (MANs) and the Internet are examples of medium to large-scale distributed systems. A novel distributed processing platform is that of a spacecraft or satellite cluster. A cluster comprises multiple spacecrafts or satellites that coordinate with each other in order to complete a task. As such, a cluster supports distributed computing. Space-based cluster-based distributed computing relies on the computational functions that are required for activities such as C^2, sensor-based data acquisition, and distributed computational algorithms. The latter induces communication requirements, hence C^4 systems.

The focus of this paper is to present a high level but detailed overview of a proposed systems model to study and investigate computationally driven requirements in spacecraft or satellite cluster environments. Distributed computations induce communication between the participating spacecrafts or satellites. The operational environment requires command and control elements. These four aspects together with their integral nature are of particular importance to us. We characterize our work as the Computation, Communication, Command and Control (C4) model wherein we emphasize the computationally driven nature of our application domain. For purposes of this paper, we further consider a motivating scenario consisting of a spacecraft or satellite cluster performing sensory acquisition and related distributed processing computations while orbiting an asteroid of six degrees of freedom of motion.

The rest of this paper is organized as follows. Section 2 describes related works, Section 3 presents a motivating scenario and Section 4 describes the proposed systems model. Conclusions are given in Section 5.

2 Related Work

There is active research and commercial technologies available relating to various aspects of spacecraft and satellite command and control. Goal or constraintbased spacecraft command and control research is described in [8]. Command and control communication links, C^3, for unmanned aircraft systems are presented in [13]. Commercial technology is also available to support C^4 systems, for example [1].

Cluster formation flying is recently deployed and continues to be a strong area of research and development. The 'Cluster' mission [3, 7] comprises four satellites flying in a tetrahedral formation designed to collectively study the magnetosphere in three dimensions, e.g. [14]. The Space based Multi-Aperture Research and Technology (SMART) [12] and the earlier TechSat-21 programs [11, 12] by the AFRL considers engineering issues involved in sparse aperture sensing. The inter-satellite distances intended to be achieved by the SMART program are significantly closer than that achieved by the Cluster mission. In [9], firefly communication is proposed as the communication protocol used between small-scale cluster spacecrafts. These systems provide multiple points of sensor acquisition but tend to have little on-board computing potential. The NASA Jet Propulsion Laboratory's Remote Exploration and Experimentation (RE&E) program considers spacecraft scalable computing systems based on MPI parallel processing [6].

Our work is different from those surveyed here. We consider a cluster spacecraft or cluster satellite as a distributed computing platform which performs computation thereby inducing communication between the cluster; the cluster requires command and control processes. Intended applications on our platform include remote data acquisition via distributed sensor arrays, the processing of such data for preliminary determination and characterization of the sensor-acquired data. We also are interested in the feedback potential of the system to reorganize and redeploy the cluster for modified or enhanced remote sensing.

3 Approach and Motivating Scenario

Inherent in the definitions of C^2, C^3 and C^4 [2] is the recognition of the integrated nature of the various constituent components. We characterize the relationship as that computation and computation are inseparable from command and control.

This research considers the scenario of deep space remote sensing of asteroids by a spacecraft or satellite cluster. In this scenario, a cluster of spacecrafts/satellites is deployed and take positions around the asteroid. We assume photographic image processing as the distributed application in this paper. The image processing application involves computation and communication; the cluster requires command and control. We emphasize that the command and control may be partially driven by the distributed application.

Computation and communication are fundamental aspects of any parallel or distributed processing application. Simple definitions that rely on the intuitiveness of these aspects are: a computation is a data synthesis procedure using mathematical or logical methods while communication is the exchange or transfer of data between processes or systems involved in computations by using some existing rules or protocols.

We propose free space optical communications between the spacecrafts/satellites in a cluster. Advantages of free optics as compared to microwave radiation [4] include: larger data rate (in the order of GB), less power consumption, smaller size and weight, higher immunity to interference in part due to the point-to-point nature of the communication, and permits denser satellite clusters due to less regional saturation of microwaves. A disadvantage is the clear line-of-sight requirements for a laser based communication system. The problems of first locating a receiver satellite and second of aligning the transmitter towards the receive stem from this disadvantage.

3.1 Motivating Scenario

The deep space asteroid scenario involves a cluster of spacecrafts or satellites that is deployed, i.e., take positions around an asteroid in deep space. The purpose of the cluster is to probe the asteroid for information. Types of anticipated sensing include imaging, radar, x-ray, infra-red imagery and physical collection of data. The satellite cluster processes information from these sensors, e.g., image processing, in a distributed computing environment. The satellites in the cluster need to communicate in order to support the computational requirements for these kinds of applications. In this paper, we consider only distributed image processing applications, and specifically, are interested in the problem of efficient multi-image composition. Figure 1 is our 'artistic' conception of this scenario with three spacecrafts orbiting the asteroid.

The spacecrafts are considered as a distributed platform that have computer systems capable of distributed processing across the cluster. Consider an imaging application where each satellite has a single camera aimed at the surface of the asteroid. At any given time, a subset of the available surface will be photographed. For example, the three spacecrafts in the middle picture of Figure 1 acquire different images of the asteroid, the two in the foreground whereas the one in the background, respectively, image the front and back sides of the asteroid. However, portions of

Figure 1. Concept illustration of multiple satellite spacecraft in orbit around an asteroid. Left: all three have line-of-sight and may communicate point-to-point. Middle: each has different orbitals, one spacecraft is behind the asteroid and its line-of-sight is occluded. Right: a later time-frame snapshot showing reestablished line-of-sight and different positional coordinates. (The Galileo spacecraft shown here replicated three times photographed Asteroid 243 Ida also shown in this picture, during its fly-by on August 28, 1993; images by courtesy of NASA and NASA/JPL-Caltech).

the asteroid are not in visible regions, for example, the 'ends' of the object. Once the three images, one by each spacecraft, have been acquired, the spacecrafts continue in their designated orbits as shown by the middle and bottom figures. The spacecrafts continue to image the asteroid thereby generating additional images which may overlap or have un-imaged gaps. The orbits of the spacecrafts perhaps should be changed, thereby repositioning the spacecrafts such that initially non-visible regions become visible. New images are taken in the new orbits. Image composition is required to piece together a single composite. There are two issues that are of interest: first, determination of non-visible and overlapping regions, and second, the repositioning such that images have overlapping boundary regions suitable for image composition algorithms. Direct study of these issues is outside of the scope of this paper.

The scenario provides us the opportunity to consider a systems model that takes into account computation (e.g. image composition), communication (e.g. exchanging image data), command and control (e.g. repositioning of satellites). We adopt the point-of-view that efficient image composition requires satellite repositioning. In general, computations require communications in order to determine command and control requirements; and command and control requires communications for global cluster maintenance.

As shown in Figure 1, all the spacecrafts in the first and and third pictures have clear line-of-sight suitable for free space optical communication. However, in the middle picture, the background spacecraft is 'behind' the object thereby interrupting the line-of-sight with the two in the foreground. In general, this may be a full interruption, or partial; if partial, then a communication protocol that allows for multi-hop communications may be useful. The resulting dynamic interconnection network is of interest in this work.

4 Overview of Proposed Systems Model

Figure 2 gives a view of the approach used in the C4 model. The Graph Abstraction model abstracts the scenario as a graph. This graph is used as the primary structure throughout the proposed systems model and has the advantage that such a generalization of the scenario could be applied to other types of missions. The C4 Interaction model and the Satellite Systems model are independent of each other while the Operations Model provides for the integration of the various components. In terms of networking, intermediate satellites are considered as routers in a dynamic interconnection network. The subsequent subsections provide overviews of each of these models.

4.1 Graph Abstraction Model

Let graph $G = (V, E)$ abstract the scenario such that V, the set of vertices, represents the set of satellites, and E, the set of edges, represents clear line-of-sight communication links. Let $P^e = \{p_1^e, \ldots, p_m^e\}$ be the edge property set associated with each edge $e \in E$. The edge property set models various aspects of the communications that are carried by the edges. Two functions, τ^a and τ^r, are defined to add edges to G, respectively, to remove edges from G. Edges are dynamically added or removed from G depending on on

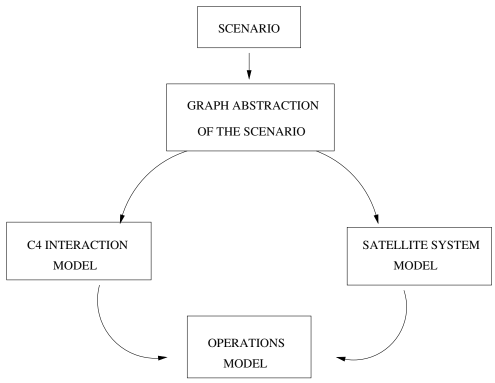

Figure 2. Approach to the C4 model

whether there is a line-of-sight exists or not, respectively.

$$\tau^a(G, e_i) : (E \bigcup e_i) \mid LOS(S_i, S_j) \text{is TRUE};$$

$$\tau^r(G, e_i) : E - e_i \text{ and } P^e - p_i^e,$$

where,

$$LOS(S_i, S_j) = \begin{cases} \text{TRUE if there is a clear line-of-sight} \\ \text{FALSE if there is no line of sight} \end{cases}$$

4.2 C4 Interaction Model

The C4 Interaction model is based on the observation that the four components: C_p (communication), C_m (computation), C^2 (command and control), are tightly coupled together. The interactions between these C4 components are modeled here.

We characterize the interactions as follows (in the following, $\rightarrow$ means 'induces'):

$$C_p \rightarrow C_m \rightarrow C^2;$$

$$C^2 \rightarrow C_m \rightarrow C_p;$$

$$C_p \rightarrow C_m \rightarrow C_p;$$

$$C^2 \rightarrow C_m \rightarrow C^2.$$

An example of the first interaction is that which was discussed earlier: image composition requires image acquisition followed by a communication followed by a repositioning of the satellites. An example of the second interaction is when a cluster maintenance is performed during image acquisition and composition. In this case, the satellites may be repositioned independent of the computational requirements of image acquisition and composition thereby necessitating new computational requirements, possibly even including additional computational loads. The third interaction captures the typical distributed computational nature of the algorithm. An example of the fourth interaction is cluster maintenance where the satellites update each other on location, movement.

We also characterize some of the types of induced communications:

1. Mission critical C^2 activity induces M-I type communication. C^2 activities may include repositioning of a satellite within in the cluster. Since this type of communication is critical to the system, message packets should be small and transfer to the other satellites must be guaranteed.

2. Mission critical computation induced C^2 activity invokes M-II type communication. In this type of communication, the internal computation of a satellite system results in the repositioning of the satellite. Computation in one satellite impacts the C^2 of the recipients.

3. Mission non-critical activity induces M-III type communication. Data transfer related communication can be classified into this category. Data transfer and reallocation of resources for system optimization constitutes this type of communication.

The interaction model is composed with the graph abstraction model. Computations are mapped to vertices and communication types to edge properties.

The use of TCP/IP protocol for transfer of data/information is chosen for this application. TCP/IP is a common set of protocols used for communication over a network. Not only has this set of protocols gained universal acceptance in terrestrial based wired and wireless systems, it has been reported to be used for communication between satellite clusters in Low Earth Orbit [10].

4.3 Satellite Systems Model

The Satellite Systems model abstracts all of the system components along with its logical functioning. This model is broadly divided into three units. The Communication Unit has all the components required for establishing, maintaining and removing a communication link. The Computation Unit is responsible for all the computations that may arise due to the effects of communication and/or command and control. The Command and Control Unit performs mission operation requirements such as thruster and motion control.

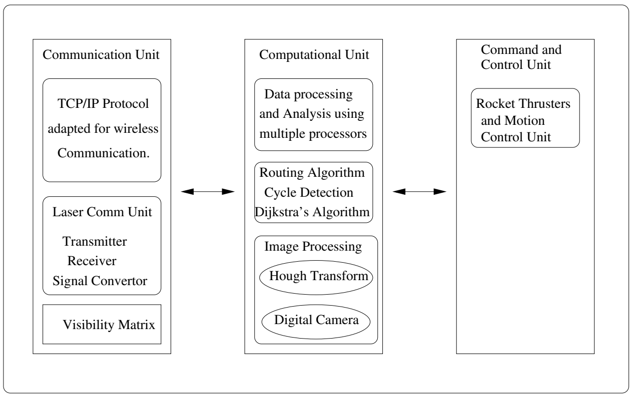

Figure 3. Satellite System Module

Satellite ID	Position	Edge
1	XYZ position	yes
3	XYZ position	no
4	XYZ position	no
5	XYZ position	yes

Table 1. Visibility Matrix for Satellite 2

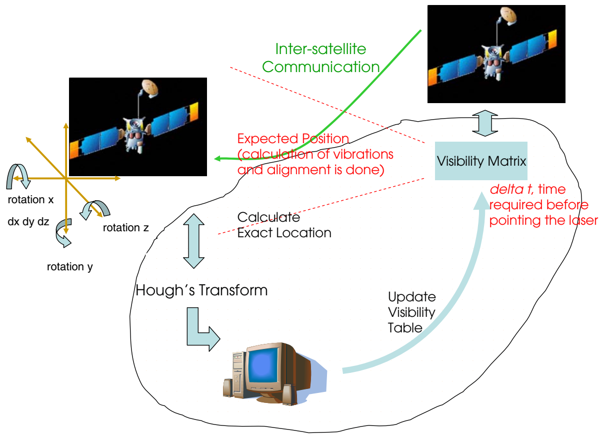

Figure 4. Operations Model (satellite image courtesy of NASA/JP).

Figure 3 illustrates the various system component units and their interactions.

The Computation Unit comprises the processors for processing the data. Besides supporting general computing requirements, the image processing sub-unit is equipped with a digital camera and related software that performs the Hough's transform for an accurate alignment of the transmitter towards a receiving satellite. This procedure assumes that a visible marking, for example, a pattern of lines or circles, exists on each satellite. The Computation Unit is also responsible for updating the active edges in the visibility matrix (discussed subsequently). Lastly, this unit also performs computations that arise due to C^2 requirements.

The Communications System comprises the systems required to perform communication transmission and reception. In particular, this system contains the visibility matrix data structure. This data structure is modeled after [10] which coarsely tracks satellites relative positions, in particular, provides for the aiming of the digital camera used for the accurate alignment of the transmitter. In essence, the visibility matrix serves a function similar to a routing table for the cluster network. Other components of the system include an optical transmitter and photoelectric receiver units. Table 1 illustrates an example of this table. The position of the satellites are relative to a particular satellite, in this case, it is Satellite 2. Positions are given in a defined coordinate system.

The scope of this paper does not include detailing the Command and Control Unit; it is included here for completeness.

4.4 Operations Model

The operations model integrates the C4 Interaction model and the Satellite systems model. Figure 4 describes the various stages of computation involved in a M-II communication. Each satellite has its own copy of the visibility matrix. Steps involved before a Type II communication takes place are: (a) Source Satellite looks up Visibility table for expected position of the destination satellite. (b) Apply Hough's Transform for calculating the exact location of the destination satellite. (c) Update the Visibility table and the routing table where required. (d) Depending upon the type of communication, encode the message and handle the marshalling of the message accordingly.

4.5 Other Issues

Vibrations in the satellite is cited as a major limitation on the performance issue of free space optical communication. Vibrations can be caused due to thrusters used for the repositioning of the satellites in the cluster. In [5], the authors cite vibrations caused due to tracking noise by the electro-optic tracker and mechanical components. We have conducted some preliminary assessment of the effects of vibration on our proposed model, and we conclude that our model is sufficiently robust with respect to vibrations.

4.6 Simulation

We have conducted a detailed although preliminary set of simulations concentrating on the issues of communication via the proposed visibility matrix in the context of feedback control for the cluster. As per the typical approaches in computer graphics, we consider a bounded region given by an ellipsoid as representing the region of space occupied by the asteroid. We compute intersections of a ray from one spacecraft to another with the ellipsoid; an intersection implies loss of line-of-sight path. The spacecrafts, visibility matrix and asteroid(s) are abstracted by suitable programming data structures. The Hough Transform is not explicitly coded. The simulation is coded in C. The simulations illustrate the first three interactions described in Section 4.2 (the fourth one does not involve computations and therefore is not of interest in this paper). In particular, the simulations confirm the feedback operational behavior illustrated in Figure 4.

5 Conclusion

This paper considers a space bourn remote sensing environment by spacecraft or satellite clusters using a dynamic free space optical interconnection network. Cluster deployment and associated functions are an emerging area of interest as is the deployment of free space optical interconnects. The C4 (Computation, Communication, Command and Control) Model that provides for a unified and comprehensive modeling of these four aspects is proposed in this paper.

This paper represents the first step in our study of a C4 system; in particular, as applied to space borne computing platforms. There is much work to be done, including, assessing the C4 model, multi-spacecraft routing and exploring system scalability.

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