A HARDWARE-IN-LOOP SIMULATION SYSTEM FOR FRACTIONATED SPACECRAFT CLUSTER

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Abstract: *Fractionated Spacecraft Cluster (FSC) is comprised of many physically independent spacecrafts orbiting in close proximity, interactively communicating via wireless network, collectively forming a loosely distributed space system. Spaceborne ad-hoc network, which provides the information exchanging physical infrastructure, is one of the enabling technologies of FSC. In this study, a Network Node Prototype (NNP) for Spaceborne ad-hoc network was built with chip Jennic5148 as its hardware. The embedded software, which based on the standard IEEE802.15.4, has three primary functions including node initialization, data transmitting control, and data receiving control. Based on four network node prototypes, a hardware-in-loop simulation system for FSC was established. a typical loose cluster flying mission was performed in this simulation system. The simulation results showed that four spacecrafts in the cluster formed a loose formation. The performance of the system demonstrated that the network node prototype effectively supported FSC self-organization control simulation.*

Keywords: *Fractionated spacecraft cluster, Spaceborne Ad-hoc Network, prototype, hardware-in-loop simulation*

1. Introduction

Fractionated Spacecraft Cluster (FSC) is comprised of many physically independent spacecrafts orbiting in close proximity, interactively communicating via wireless network, collectively forming a loosely distributed space system. It changed the concept of traditional monolithic spacecraft. In the traditional approach, spacecraft are tailored to each mission and are associated with high risks and costs and long cycles. While, in fractionated spacecraft cluster, a plurality of reconfigurable spacecraft modular on orbit forms a spacecraft system in space, instead of being integrated into a complete spacecraft in the manufacture plant. Meanwhile, the reconfigurable modular could be high-volume manufacturing, launched separately, free to interact. Those properties endow fractionated spacecraft cluster with many advantages such as capability of system reconstruction, flexibility of mission accomplishment, replaceability of specific unit, and robustness of malfunction [1,2].

Fractionated Spacecraft Cluster can be applied to Earth observation, space exploration, and other space fields. Ref. [3] presented the Magnetic NanoProbe Swarm mission utilizing a constellation of several swarms of nano satellites in order to acquire simultaneous measurements of the geomagnetic field resolving the local field gradients. The space segment comprised of up to 4 S/C swarms each consisting of up to 6 nano satellites and 1 mother spacecraft. The Autonomous Nano-Technology Swarm (ANTS), fractionated spacecraft cluster mission proposed by NASA, involved a swarm of autonomous pico-class spacecraft that would explore the asteroid belt [4-6]. Another asteroid explore project APIES(Asteroid Population Investigation & Exploration Swarm) is a “swarm” mission developed by EADS Strium, based on the utilization of 20 spacecrafts including one HIVE(Hub and Interplanetary VEhicle) and 19 BEEs(BElt Explorers) working cooperatively to finish the overall mission objectives [7].The Defense Advanced Research Projects Agency (DARPA) has commence an space system plan F6 – short for Future Fast, Flexible, Fractionated, Free-Flying Spacecraft, F6 plan provided a future-oriented spacecraft architecture, which disassembles the traditional monolithic spacecraft into a combination of separate modules. Each separate module can be batch manufacturing, separately launched. Those modules which kept in a cluster flight formation on orbit, exchange information through wireless communication, and transfer energy through wireless transceiver, constitute a fully functional virtual cluster spacecraft. F6 plan can be seen as a true primary fractionated spacecraft cluster [8].

Information exchange among the fractionated modulars is one of the important constituents of F6 Plan. Similarly, the information exchange is the enabling technology for the effectively operation of FSC. To fulfill the system reconstruction, flexibility of mission accomplishment, replaceability of specific unit, and robustness of malfunction, it is necessary for the information exchange network to be flexible, reconstructive and robust. The wireless ad-hoc network is a infrastructureless mobile network, that have no fixed routers, all nodes in the network can be connected dynamically in an arbitrary manners. Nodes of these networks function as routers, which discover and maintain routes to other nodes in the network, and as terminals at the same time [9-11]. These features of ad-hoc network make it very suitable for spacecraft cluster.

In this paper, we built an wireless ad-hoc network node. And based on the nodes as the spacecraft cluster network node prototype, a hardware-in-loop simulation system for fractionated spacecraft cluster was established. The objective of the system is to build a demonstration platform for analysis and simulation of the cluster operation, individual spacecraft control, information exchange, and so on, Finally, a task simulation of loose flight formation including four spacecrafts was performed on that demonstration platform.

2. The wireless ad-hoc network node prototype

The wireless ad-hoc network node has two communicate mode, peer-to-peer or broadcast. In peer-to-peer mode, a message from source node will be transmit to the destination node via intermediate nodes chosen according to the route protocol. While in broadcast mode, a node broadcasts message and its neighbor nodes can receive that message at the same time. The wireless ad-hoc network node prototypes is composed of communication hardware and embedded control software.

2.1. Development of the communication hardware

The communication hardware (Fig. 1) includes wireless transceiver chip and interface expansion board. The wireless transceiver chip, as the core part of the hardware, receives radio signals, processes the received signals and transmits the generated signals. The function of the interface expansion board is to provide power and interactive interface for the wireless transceiver chip.

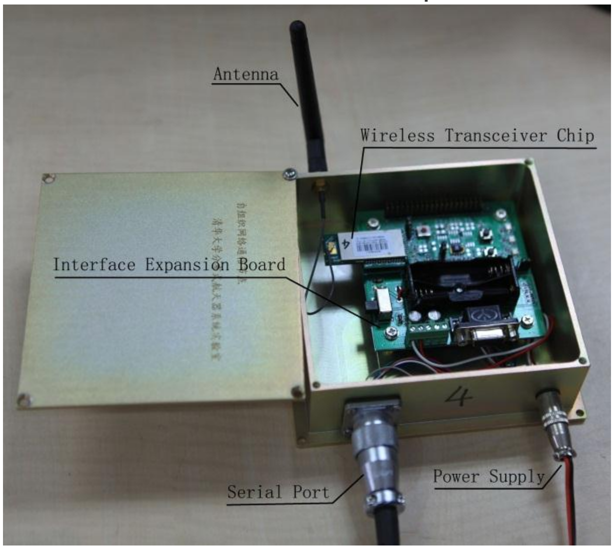


Figure 1. Wireless ad-hoc network node prototype

In order to simplify the complexity of the design process, we selected commercial on-shelf product Jennic5148 module as the wireless transceiver chip. Jennic5148 module is a ultra low power, high performance surface mount RF chip with large memory, high CPU and radio performance and all RF components included. It has a 32-bit RISC CPU allowing software to be run on chip, 128kB ROM to store program code, 128kB RAM to store system data, 3 system timers, 2 UARTs. The RF components operates in the 2.4GHz frequency band which is internationally free radio frequency band.

The interface expansion board is comprised of a group of switches, buttons, serial interface, external power connector, etc. It has two operation mode including development and transceiver. Under development mode, it is used to inject the compiled binary embedded control program file into the wireless transceiver chip through the serial port. Under transceiver mode, it allows Jennic5148 module to send and receive data in accordance with the control program.

2.2. Design of the embedded control software

The embedded control software, which was developed based on the standard IEEE802.15.4, has three primary functions including node initialization, data transmitting control, and data receiving control. Node initialization function，running as soon as power-on，sets all parameters involved node identity, communication channel, and so on. Data transmitting control function, triggered by interrupt timer periodically, checks whether the sending data buffer has data to transmit and sends the data. Receiving control function, enclosed in a overall loop, processes the received data. The flowchart of embedded software is shown in Fig. 2.

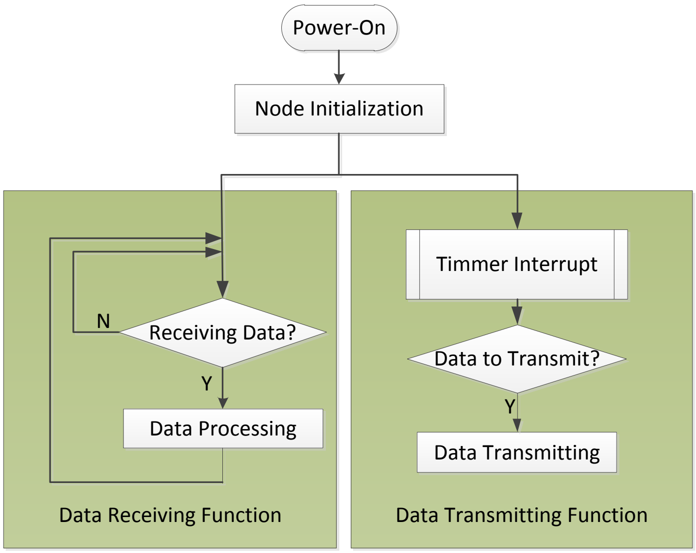


Figure 2. Flowchart of the embedded software

Especially, a frame matching approach was adopted to discriminate the repeated data frame, which might be caused by the multipath effect or other instable factors. Frame matching approach was illustrated in Fig. 3. The transmitting node i counts the frames it has transmitted to receiving node j. And when node i transmits a frame to node j, it enclosed the transmitting sequence number j in the frame head. The receiving node sets a received counter for each node, e.g. in Fig. 3, the received counter for node i is i. When it received a data frame from node i, it firstly check the frame head and pick up the transmitting sequence number j. Then it compares the quantity of the transmitting sequence number j and the received counter i. If i is greater than j, the receiving frame must be a repeated frame and must be discarded. If i is smaller than j, it could be concluded that some data frames must have been missed. To acquire the missed data frames, the receiving node might send retransmission request to the sending node. If those data frame are not need to retrieve, the receiving node j assigns the value of $j+1$ to the receiving counter i to ensure the next data frame could be received correctly. If i is equal to j, the receiving data frame is correct. Via the frame matching approach, the receiving node could determine whether the receiving data frame is in correct sequence, discard the repeated frame and retrieve the missed frame.

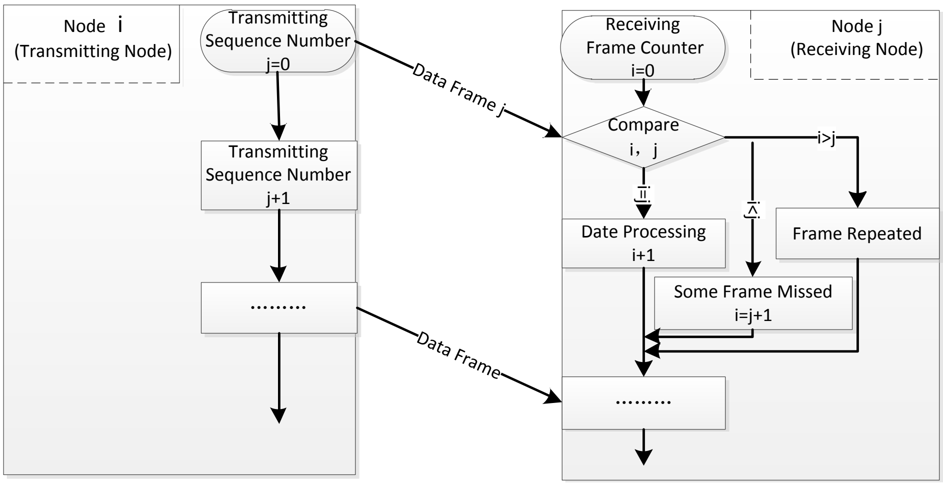


Figure 3. Frame matching approach

3. The overall structure of the simulation system

Based on four network node prototypes, a hardware-in-loop simulation system for FSC was established. Besides the network node prototype, the simulation system was comprised of On-board Computer Simulator (OCS) and Dynamical Simulator (DS). Figure 4 shows a photo of the hardware-in-loop simulation system for FSC. And Figure 5 illustrates the architecture of the simulation system. The architecture of the simulation system could be divided into three parts, the Information Exchanging Platform (IEP), Spacecraft Prototype (SP) and dynamical simulation environment. The information exchanging platform, consisted of the four network node prototypes, provided the information intercommunication for on-board computer simulators. The on-board computer simulator was used to produce the control instruction according to the predefined control scheme and the information received from the information exchanging platform. The dynamical simulator, connected to the on-board computer simulator via serial port, calculated the orbital data for spacecraft prototype. It received the control instruction from the on-board computer simulator, evolved the next orbital data, and sent the orbital data back to the on-board computer simulator.
The simulation system used XPCTarget, a Matlab toolkit for real-time signal acquisition and control application, as the simulation environment development software platform. XPCTarget runs in a host computer connected with the four on-board computer simulators and the four dynamical simulators via a network switch. The programs for the on-board computer simulators and the dynamical simulators were developed in the host computer firstly. Especially, the programs for the on-board computer were specially developed for specialized tasks. While the programs for the dynamical simulators could be universal for different tasks. Those programs must be

downloaded to the on-board computer simulators and the dynamical simulators beforehand. Once a simulation was started, the host computer would not interfere with the operation of the simulation and the process of the simulation ran entirely in accordance with the programs in the on-board computer simulators.

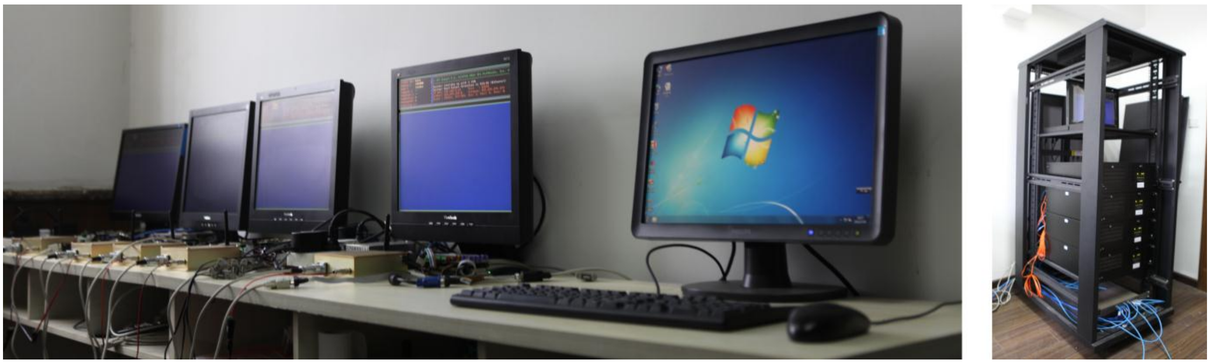
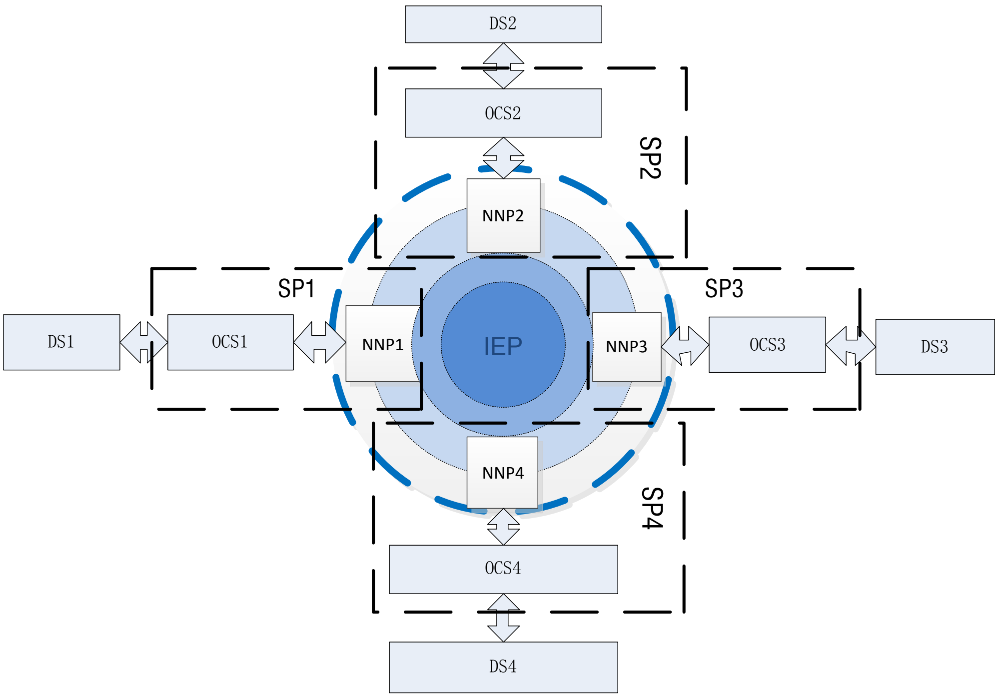


Figure 4. Hardware-in-loop simulation system for FSC



IEP: Information Exchanging Platform. NNP: Network Node Prototype.
DS: Dynamical Simulator. OCS: On-board Computer Simulator.
SP: Spacecraft Prototype.

Figure 5. Architecture of the hardware-in-loop simulation system for FSC

4. Loose cluster flight demonstration

Loose cluster Flight, which might be a common flight mode for fractionated spacecraft cluster, do not require spacecraft to maintain precision relative station-keeping, but only to keep the distance between two spacecrafts within a certain range to ensure that spacecrafts can communicate, and to ensure no collision risk between spacecrafts. On the simulation platform, a task simulation of loose flight formation including four spacecrafts was performed.

4.1 Information exchange scheme

The information exchanged between the on-board computer simulators included the spacecraft ID, the reference spacecraft ID, control marking, time stamp, and the position and velocity of a spacecraft, illustrated in Fig.6. The spacecraft ID was an unique identity number for each spacecraft, and was used to determine the information source. The reference spacecraft ID denoted whether the spacecraft was the center of the cluster and other spacecrafts in the cluster should flight referring to its orbit. The control marking marked the control state of a spacecraft. When the distance between two spacecrafts was too close to be in collision risk or is too far to lose wireless communication, they would control themself to change the distance. The time stamp recorded the running time from the simulation starting. The position and velocity of a spacecraft, corresponding to the time stamp, were acquired from the dynamical simulator.

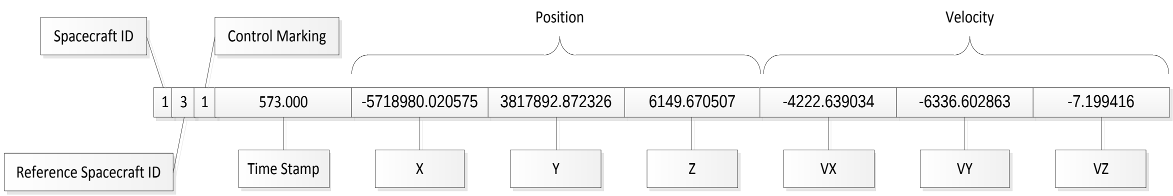


Figure 6. Information exchanged between on-board computer simulators

Each spacecraft in the cluster broadcasted its information. Thus, each spacecraft could receive information of other spacecrafts within the wireless communication range. To simplify the demonstration, here the hypothesis that the four spacecrafts could always receive information from each other was adopted.

4.2 Spacecraft control scheme

The spacecraft cluster control scheme included two rules: the reference spacecraft determining rule and the follow position rule. The reference spacecraft deremining rule chose the spacecraft near to the center of the cluster to be the reference spacecraft. According to the follow position rule, other spacecrfts in the cluster could calculated their sequence in the cluster respectively. The detail of the rules was discussed in Ref. [12]。

4.3 Demonstration scenary

To validate the simulation system, a typical loose cluster flight demonstration was performed on that simulation platform. The cluster flight scenery began at 12:0:0, June,1st, 2008. And the initial orbit parameters of four spacecratfs were listed in table 1.

Table 1. Initial Orbit Parameters of the Cluster

Spacecraft ID	1	2	3	4
Orbit altitude（km）	600	610	620	630
eccentricity	0	0	0	0
Orbital inlination（degree）	97.4825	97.4825	97.4825	97.4825
The longitude of the ascending node	9.7797	9.7787	9.7777	9.7767
Argument of perigee	0	0	0	0
Mean anomaly	100.1	100.2	100.3	100.4

Figure 7 displayed the simulation results and it is obvious that the four spacecrafts formed a loose formation.

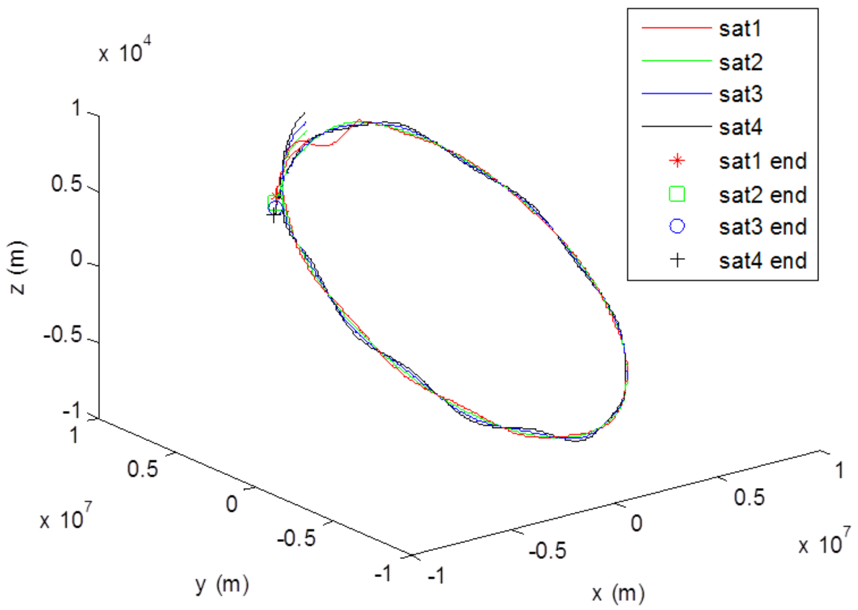


Figure 7. Result of loose cluster flight demonstration

5. Conclusions

a Network Node Prototype (NNP) for Spaceborne ad-hoc network was built with chip Jennic5148 as its hardware. Based on four network node prototypes, a hardware-in-loop simulation system for FSC was established. A typical loose cluster flying mission, with distributed following and queuing tactic adopted to manage each

of the four spacecrafts, was performed in this simulation system. The simulation results showed that the four spacecrafts formed a loose formation. The performance of the system demonstrated that the network node prototype effectively supported FSC distributed control simulation.
The hardware-in-loop simulation system established an control strategy testing platform, it could be utilized to evaluate the collective behavior of spacecraft cluster in the future.

6. Acknowledgements

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7. References

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