Micro-Navigation Satellite Network Design and Analysis

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BIOGRAPHY

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ABSTRACT

Accurate position and orientation data are the bases for successful navigation. In this paper, we design and analyze the micro-navigation satellite network that share orientation information among the satellite network. Satellites use GPS, IMU and lasers to align with each other, transferring and sharing the accurate absolute and relative orientation information. Our design includes a GPS and IMU navigation data fusion procedure, and an orientation information transfer process which uses lasers and radio frequency links. We propose to use two parallel laser beams to transfer attitude data between satellites. Then we analyze this design by modeling the micro-navigation satellite network using an epidemic model. We show that the orientation accuracy of all satellites in the constellation improve using this procedure. We also design the communication protocol and scheduling algorithm as well as the laser targeting and control algorithm. Then, we performed the ground experiments to verify the feasibility of the GPS/IMU data fusion are discussed in the paper.

INTRODUCTION

Using networked small satellites to perform space missions instead of one large satellite has a number of advantages. Small satellite network is more cost-effective, more scalable, and more robust compared to the single satellite system. Satellite control applications such as self-organized satellite network and formation control, autonomous docking, have been actively investigated in recent years [Beard et al. 2000, Inalhan et al. 2002, Kapila et al. 2000, Mesbahi et al. 2001, Won et al. 2003]. One of the critical areas for the satellite network control is to determine the position and orientation of the satellites. In the satellite network, it is important that the satellites perform the tasks autonomously and cooperatively, thus the satellites usually not only need to know their own navigation information, but the navigation information of their neighboring satellites. In a constellation which consists of a number of the satellites, however, the navigation system of each satellite provides position information and orientation information. This navigation information is absolute navigation information because each satellite obtains the information individually. Because of the restrictions on size, weight, onboard computation resource, and the cost, the small satellites do not always have accurate navigation subsystems. The navigation accuracy of each satellite may be different. Thus the relative orientation and position error are closed related to the navigation error of each satellite and is typically much larger. This characteristic limits the constellation performance, where the accurate relative orientation and position between satellites are critical. Thus, the navigation performance of the small satellite network is difficult to be guaranteed.

In addition, sharing an accurate relative position and orientation information provides a way by which the navigation accuracy can be transferred from one satellite to another. To illustrate this, assuming there are two satellites in the network, one satellite, which we call the reference satellite, has higher accurate orientation and position information for itself, the other satellite, which we call the target satellite, has lower accurate information. If the relative position and orientation between the reference satellite and the target satellite can be obtained with a higher accuracy compared to the target satellite's own navigation information, the target satellite can then improve its navigation accuracy by using both the navigation information from reference satellite and the relative navigation information. Therefore, it is necessary to find a method which can determine an accurate relative orientation and position information for the satellites in the network. In this paper, we propose a novel method called Micro-Navigation Satellite Network, by which a satellite network determines the accurate relative navigation information between satellites, as well as sharing the accurate orientation information in the network. We achieve this by transferring position and orientation data via RF links and laser links.

The organization of this paper is as follows. Next section introduces the design of the Micro-Navigation Satellite Network. In the subsequent section, the satellite network performance is analyzed. And the simulation results for the orientation information model are given. Then the implementation of the prototype testbed is introduced and the future work is discussed. The conclusions are given in the last section.

MICRO-NAVIGATION SATELLITE NETWORK DESIGN

One method that we have proposed to solve the problem described in the last section is the Micro-Navigation Satellite Network (μ−NSN). The μ−NSN consists of a number of networked small low earth orbit (LEO) satellites. The μ−NSN provides a way to acquire, share and transfer the navigation information among the satellites in the network. To achieve this goal, each satellite in the μ −NSN has a navigation data determination subsystem, which consists of a Global Positioning System (GPS) receiver, a solid state inertial measurement unit (IMU), two lasers, and a lens with a charge-coupled device (CCD) image sensor, a number of photodiodes, and a radio frequency (RF) communication module. The GPS and IMU are used for position and orientation acquisition, RF module is for navigation information sharing; two lasers, lens with CCD sensor, and photodiodes are used to establish the laser links with other satellites to transfer the orientation information. We introduce the orientation information transfer method for the μ−NSN. Because that the IMU is an inertial device, which has the accumulating error with time, the accuracy of the orientation information from IMU keeps decreasing without a bound if there is no additional way to calibrate orientation information. With the orientation information transfer method, a reference satellite, in the μ −NSN transfers its higher accuracy to a target satellite with lower accuracy to calibrate the orientation of the target satellite. After the transfer, the calibrated satellite which obtains higher accurate orientation information can also transfer its orientation accuracy to the satellites with lower orientation accuracy. As this procedure repeats, more and more satellites with low accurate navigation information get calibrated, the overall constellation navigation capabilities are improved.

- ***General Methodology***

The orientation information transfer procedure is as follows. A reference satellite knows its accurate position and orientation. It controls two gimbaled lasers to point to another satellite, the target satellite. At the same time, the reference satellite broadcasts its orientation information via radio frequency (RF) links to other satellites. If the optical sensor of the target satellite detects two laser beams from reference satellite, the laser link between two satellites is established. And the target satellite is aligned with the reference satellite. We use two lasers to establish a link between two satellites to align a satellite with low orientation accuracy from a satellite with high orientation accuracy instead of one laser assembly. The reason is to eliminate the ambiguity in determining the relative orientation between two satellites. Because of the good directive property and small divergence angle of the lasers, the relative orientation between two satellites is determined accurately. The target satellite receives the absolute navigation information from the reference satellite via RF link, and the relative orientation information between reference satellite and the target satellite is determined by the laser links, then the target satellite can calculate its own absolute navigation information by combining the absolute navigation of reference satellite and the relative orientation information between reference satellite and the target satellite, which is a part of the target satellite navigation data fusion. By this means, the accurate relative navigation information is obtained and the navigation accuracy is transferred from the reference satellite to the target satellite.

Figure 1 shows the procedure of orientation information transfer. The figure also shows that the relative orientation between two satellites can be determined uniquely by the two lasers. If the orientation of one satellite changes, the laser image spots on the CCD change accordingly. Furthermore, after obtaining the accurate orientation information, the aligned satellite will act as a reference satellite to transfer reliable orientation information to other satellites with lower orientation accuracy. Here, we make an important assumption about the satellite network; there is initially a small number of satellites in the network which have highly accurate navigation subsystems and can maintain the navigation information at a highly accurate level. These satellites can always align other satellites to transfer their orientation information and are considered as the permanent reference satellites in the network. This assumption is necessary to avoid the situation where all satellites eventually decay to the lowest orientation accuracy if there are no external sources providing the accurate orientation information. If we assume that there are no reference satellites, then the orientation accuracy will decay with time, because all satellites have accumulated orientation error.

We notice that the procedure described above is similar to the dissemination of an epidemic disease. In an epidemic, an infected individual can infect other susceptible individuals. Once a susceptible individual is infected, it becomes infectious and can infect other susceptible individuals via contact. Similarly, in a satellite network, a reference satellite can align a target satellite with laser. Then the target satellite acquires accurate relative and absolute orientation information. Because of this similarity, a modified epidemic model is used to represent μ−NSN system. To better describe the different accuracy of the satellite, we discretize the orientation accuracy to ten confidence levels. Higher confidence level represents higher orientation accuracy. Then a multiple confidence levels μ −NSN model is proposed to analyze the orientation information transfer of the satellite network. The preliminary results with three confidence level case has been presented in [Kang et al. 2007]. The possible applications of this technology are synthetic aperture radar, space based interferometry, multipoint observation, and distributed aperture reconnaissance, where accurate relative position and orientation information is needed.

To increase the probability of laser targeting and shorten the acquisition time when establishing the laser alignment, we developed a two-stage alignment method. The photodiodes which are mounted around the target satellite body, work as the coarse laser detector. The lens and CCD image sensor work as a relative orientation estimator, which calculates the relative orientation between two satellites. At the first stage, the reference satellite uses wide field of view defocused laser beams to

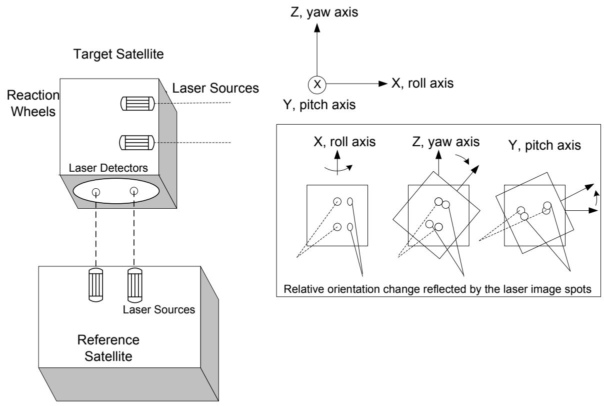

Figure 1. Orientation Information Transfer.

locate the target satellite. If one of the photodiodes detects the incident laser beams from the reference satellite, it broadcasts an acknowledgement to the network and the second stage begins. The reference satellite sends the focused beam towards the target satellite and the target satellite changes the optical lens' orientation to face towards the reference satellite. Once the laser hits the lens the CCD on the target satellite will compute the new orientation from the reference satellite's orientation information. We use a line-of-sight relative orientation determination algorithm to calculate the relative orientation. Then the target satellite uses this information and the absolute reference information received via RF link to calibrate its own absolute orientation information.

- ***Laser Targeting and Alignment***

How the satellites choose to transfer the navigation information to other satellites is a scheduling issue. We will address the scheduling issue in this subsection. The purpose of scheduling algorithm is to find optimal laser source and target to increase overall navigation confidence level. The target satellite is determined based on the difference of confidence level with source satellite. All satellites have the responsibility to compute and store the necessary navigation data in the memory. In this section, we sketch the algorithm of networked system. The algorithm involves the following three major phases:

- Initialization,
- Position and confidence level report (Reinitialization),
- Laser alignment.

Initialization
In the initialization phase, a satellite keeps an empty data table. The table contains the satellite identification number (ID), GPS time, confidence level and altitude, longitude, latitude data section of each satellite. To obtain

confidence level and position of other satellites, a satellite conducts initialization phase.

Step 1: Every satellite broadcasts a navigation message.

Step 2: If a satellite receives a navigation message, it checks a message identifier to see if a message has been received before. If yes, it simply discards a message, otherwise, it stores the information and forward. The message is forwarded according to the flooding policy and this process continues until a message is discarded. When all the satellites obtain a full data table, the initialization phase is complete.

Position & Confidence Level Report (Reinitialization)
Because confidence level drops with time, navigation messages need to be sent out periodically. If a satellite updates its confidence level due to the laser alignment, a satellite also sends out navigation messages. In both cases, a satellite performs reinitialization phase. During this phase, if confidence level is changed, a satellite immediately reports a changed confidence level to other satellites using a navigation message. The message propagates using a similar method described in the previous subsection.

Laser Alignment
A laser alignment procedure is given as follows. Two satellites are participating in the alignment process. One is the reference satellite and the other is the target satellite. The reference satellite obtains the navigation information of the target satellite via communication link. Then, the reference satellite controls two gimbaled lasers to point to the location of the target satellite. However, due to the accuracy of the GPS devices, the reference satellite may not be able to locate the exact position of the target satellite in the beginning. The uncertainty of the exact position of target satellite causes a field of uncertainty (FOU) at the reference satellite side, where the probability of the target satellite falling into the FOU is related to the area of the FOU. We assume that the area of FOU is square shaped. Then we choose the area of FOU to ensure the acceptable alignment probability.

The reference satellite is equipped with the focus adjustable lasers, meaning that it can adjust the beamwidth of the lasers. At the first stage, which we call coarse alignment stage, the reference satellite defocuses the laser beam to produce a wider laser beam. Then, the reference satellite uses this wide beam to sweep the FOU for the target satellite. The scanning strategy can be chosen flexibly. Here we use the center-out scanning pattern shown in Figure 6. At the first scan position, the reference satellite points the laser beam to the target satellite such that the boresight axis intersects with the pre-obtained target satellite position. If the target satellite does not sense the laser beam, which means that the actual position of the target satellite falls outside the area where the reference satellite expects it to be, then the reference satellite adjusts the gimbal to control the laser beam revolving from the first scan position to outside. If the laser beam hits the sensors on the target satellite during this process, which means that the actual position of the target satellite is discovered by the reference satellite, the coarse alignment is established between reference satellite and the target satellite. The target satellite informs the reference satellite about the hit via RF communication link, then the system goes into the second stage, fine alignment stage. At this stage, the reference satellite holds the orientation of the lasers while shrinking the beamwidth of lasers. The focused laser beam guarantees the fine alignment accuracy, and consequently, the obtained orientation accuracy. In the mean time, the target satellite adjusts its attitude according to its coarse sensor readings. The purpose of this attitude adjustment is to point the fine sensor of the target satellite towards the incoming laser beams. Once the two laser beams both fall into the detector field of view of the fine sensor (the range of the lens). According to the optical principle, two point sources at a distance which is far greater than the focal length will converge to two image points at the focal plane when passing through a convex lens. And the four points lay in the same plane. Therefore, the target satellite can distinguish the two image points from the CCD installed at the focal plane to calculate the relative orientation between the reference satellite and the target satellite, as illustrated in Figure 2. Because that the target has obtained the absolute orientation of the reference satellite with respect to the earth fixed coordinate before the alignment process, then, it can compute its absolute orientation using the information from the relative orientation and the absolute orientation of the reference satellite. Thus, via laser alignment process, the accurate orientation information of the reference satellite is transferred to the target satellite.

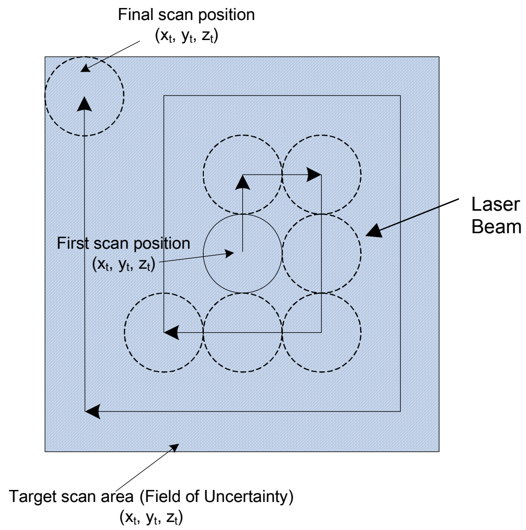

Figure 2. Laser Scanning Pattern.

- ***Navigation Data Fusion***

We assumed that each satellite in μ−NSN is equipped with a GPS receiver and an IMU. The output data from GPS and IMU is fused to generate the optimal navigation data.

The μ−NSN navigation data fusion includes two levels. First level is the GPS/IMU data integration. The second level is the GPS/IMU/Laser alignment.

GPS provides a satellite the following information.
  - Longitude & latitude
  - Ground Speed
  - Heading (relative to True North)

IMU provides the following information.
  - Tri-axis accelerations
  - Tri-axis angular rates
  - Yaw, Pitch & Roll

When there is no laser alignment, satellites perform GPS/IMU data fusion to keep their position and orientation accuracy in a specific range. The data fusion using GPS and inertial devises has been studied by many researchers at different level [Alison et al. 2004, Wang et al. 2003, Mohamed et al. 1999]. In this paper, we use a knowledge based data fusion to fuse the GPS data and the IMU data [Liu 2008]. See Prototype Implementation Section in the sequel.

After the laser alignment is established, the satellite navigation data fusion system switches to the second level, GPS/IMU/Laser alignment. The target satellite determines its relative orientation with respect to the reference satellite according to the laser image caught in the CCD sensor. It also received the absolute orientation information of the reference satellite at the time of alignment. Then, it uses calculated relative orientation information and the absolute reference orientation to calculate its own absolute orientation. Then the target satellite compares the calculated orientation information to the information measured by its own GPS/IMU sensor. There is difference between these two values which is caused by the difference of the accuracy. The target satellite then uses the calculated orientation information to correct the measured readings from GPS/IMU set to accomplish the second level data fusion. After this calibration, the target satellite obtains the higher orientation information and the system switches back to the first level data fusion.

- ***Communication Architecture and Networking***

The μ−NSN is a fully distributed network. Every satellite has the responsibility to compute and store the navigation data independently. Then, how to share the individual navigation information is considered in the network and communication architecture design. According to the flexible constellation configuration, we designed two different network architectures for the μ−NSN, one is connectionless scheme, and other is connection-oriented scheme. For both cases, we developed the network communication protocols, which will be used during the orientation information transfer.

In connectionless scheme, messages are forwarded using flooding policy without considering which links they are going on. In connection-oriented scheme, messages are transmitted from source to target only after the laser alignment is established and the frequency is allocated. Using these two different methods, messages can be quickly delivered during initialization and re-initialization phases. Furthermore, messages can be transferred with high Quality of Service (QoS) from source to target.

We develop the application layer including various types of message. For transport and network layer, we consider Internet protocols (TCP/IP and UDP/IP). We also provide communication issues of delay as TCP/IP is involved in our system. In this project, the link and physical layer are not our main concern. Thus we only consider high-level data link control (HDLC) framing over RF link for these last two layers.

Reference and target satellites comprise the orientation information transfer network. In the system, reference satellites keep highest confidence level using additional sensors such as a GPS receiver and a star tracker. Because of its high confidence level, reference satellites always have high attitude accuracy. If the attitude determination accuracy of target satellites degrades with time due to the low sensor performance, then the errors are compensated by laser alignment from the reference satellites or other higher confidence level target satellites. Moreover, in order to have accurate relative position and orientation accuracy between satellites, the satellite navigation network is critical. All satellites in the network must report confidence levels and navigation information (e.g. GPS data or Inertial Measurement Unit (IMU) data) to other satellites. Satellites also request to open or close the laser alignment session. To make these services available, three types of message forms—navigation, request, and response—have to be defined between satellites equipped with a GPS receiver for the orbit determination and an IMU for attitude determination.

These three messages consist of common message header and message body. The common message header contains basic information for communication between satellites to satellites, and message body includes sensed information or actual functions to be performed.

Message Header

The common message header has the following format as shown in Table 1. We define this format based on the recommendation from the Consultative Committee for Space Data Systems (CCSDS) [CCSDC 1997, CCSDS 2002].

Table 1. Fixed Message Header Fields

Field	Length (bits)	Value	Comments
Version	2	'00'	The current protocol version is 0. We reserve 2-bit for new version.
Message identifier	5	#####	This field uniquely identifies a message transaction to prevent multiple deliveries.
Message type	1	0 – Navigation 1 – Request/ Response	This field distinguishes the message type between navigation message and request / response message.
CRC Flag	1	'0' – not present '1' – present	The CRC field is a cyclic redundancy check that detects errors in the rest of the frame. If CRC option is active, a satellite set CRC flag to 'true' and calculate and insert CRC in each outgoing message.
Message length	6	0 to 47 bytes	This field limits the message length. The length includes both header length and body length. Since this is 6-bit in octet, it limits a maximum message length to 47 bytes.
Reserved	1		Reserved for the future use

Navigation Message Body

The navigation message contains confidence levels and sensed position and orientation data. The satellites share position and attitude information using navigation messages. Table 2 shows the navigation message body field.

Table 2. Navigation Message Body

Byte offset	Field	Length (bits)
0	Roll	32
4	Pitch	32
8	Yaw	32
12	Altitude	32
16	Longitude	32
20	Latitude	32
24	Heading	32
28	GPS time –Year	32
30	GPS time – Month	16
32	GPS time – Day	16
34	GPS time – Hour	16
36	GPS time – Minute	16
38	GPS time – Second	16
39	Attitude Confidence level	8
40	Position Confidence level	8

Request / Response Message Body

The satellites shall issue a request message to open / close laser alignment session or request navigation information. The response message is issued for the reply of the request message. Below represents our request / response message body with detailed condition codes.

Table 3. Four Bit Condition Codes

Condition Codes (binary)	Condition
'0000'	Request to open laser alignment session
'0001'	Response to open laser alignment session, OK
'0010'	Busy to open laser alignment session
'0011'	Laser alignment successfully is finished
'0100'	Laser alignment is failed
'0101'	Request navigation information
'0110'	Request to close laser alignment session
'0111'	Response to close laser alignment session, OK
'1000'	Cycle redundancy check (CRC) failure

MICRO-NAVIGATION SATELLITE NETWORK ANALYSIS

If μ−NSN works as designed, then will this improve the navigation capability of the constellation? This is the question that we will investigate in this section. We will investigate the orientation accuracy because the position information obtained via GPS has the bounded error.

We analyze the orientation information transfer (OIT) process in the μ−NSN to determine whether this process will improve the orientation accuracy of the satellites in the constellation. First, we develop a ten confidence level orientation information transfer model. Second, we analyze the steady state behavior, and finally we perform simulations to verify the analysis.

We apply the concepts of epidemic model to the OIT problem. The spread of viruses may be modeled using differential equations [Anderson et al. 2000, Kermack et al. 1927]. We modify this epidemic model for OIT transfer problem. Assuming that the total number of satellites is a constant, denoted by *M*, we divide the satellite orientation information into ten confidence levels according to its orientation accuracy. The highest confidence level is denoted by confidence level ten or CL10. The lowest confidence level is confidence level one or CL1. The nodes with higher confidence level can always transfer its orientation information to other nodes with lower confidence levels. It should be noted that the decay of the orientation accuracy is in fact a continuous process. We discretize this continuous orientation accuracy to ten discrete levels in order to model the OIT process using a modified epidemic model. The error due to the discretization could be reduced by introducing more confidence levels.

Other OIT parameters include the alignment rate, decay rate and the proportion of the permanent reference nodes. The alignment rate represents the successful orientation information transfer using the laser between nodes. This is similar to the contact rate in the epidemic model. Nodes in the higher confidence level will degrade to the lower confidence level at the certain decay rate because of the accumulated orientation error in IMU, which corresponds to the recovery rate in epidemic model. The proportion of the permanent reference nodes is actually the initial proportion of nodes in CL10, because that only the permanent reference nodes can keep themselves in CL10 before the laser alignment process begins. Let $L_i(t)$ be the number of the satellites in CL*i* at time *t*, and proportion of satellites in CL*i* at time *t* is given as $l_i(t) = \frac{L_i(t)}{M}$. We use $l_i(t)$ instead of $L_i(t)$ in the later analysis. We assume that there are initially some satellites with CL10 in the OIT model acting as the reference nodes, these satellites are equipped with highly accurate navigation subsystems and can always maintain their confidence level at CL10. These reference nodes may be satellites with multiple star trackers. The rest of the nodes belong to CL1 to CL9, and these are the satellites without highly accurate navigation subsystems such as MEMS inertial measurement units (IMU). The initial conditions of the OIT model are $l_{10}(t_o) \in (0,1)$, $l_1(t_o)$, $l_2(t_o)$, …, $l_9(t_o) \in [0,1)$. The laser alignment is established between reference nodes and other nodes, however, alignment information transfer occurs when the confidence level of reference node is higher than the confidence level of the target node. Once an aligned satellite updates to more accurate orientation information, it can also act as a reference node to align other nodes in the network. We define the laser alignment rate λ as the number of alignment between any two nodes per unit time.

Due to the accumulated orientation errors caused by IMU in the satellites, Except for the reference nodes which have accurate navigation subsystems, the orientation accuracy of all other nodes will decay along with time, nodes in CL*i* will lose their confidence level after some time and degrade into CL$(i-1)$, at the decay rate γ_i per unit time.

Next, we give the mathematical model for the ten confidence level OIT system. To simplify the analysis, we assume that the decay rates are identical among all levels, i.e. $\gamma_2 = \gamma_3 = ...\gamma_{10} = \gamma$.

The ten confidence level OIT model can be represented as

$$\begin{aligned}
\dot{l}_1(t) &= -\lambda l_1(t)(l_2(t)+l_3(t)+...+l_{10}(t))+\gamma l_2(t) \\
\dot{l}_2(t) &= \lambda l_1(t)l_2(t)+\gamma l_3(t)-\lambda l_2(t)(l_3(t)+l_4(t)+...+l_{10}(t))-\gamma l_2(t) \\
\dot{l}_3(t) &= \lambda l_1(t)l_3(t)+\lambda l_2(t)l_3(t)+\gamma l_4(t)-\lambda l_3(t)(l_4(t)+l_5(t)+...+l_{10}(t))-\gamma l_3(t) \\
&\vdots \\
\dot{l}_9(t) &= \lambda l_9(t)(l_1(t)+l_2(t)+...+l_8(t))-\gamma l_9(t)+\gamma(l_{10}(t)-l_{10}(t_o)) \\
\dot{l}_{10}(t) &= \lambda l_{10}(t)(l_1(t)+l_2(t)+...+l_9(t))-\gamma(l_{10}(t)-l_{10}(t_o)).
\end{aligned} \tag{1}$$

And the performance index is represented as:

$$P(t) = l_1(t)+2\times l_2(t)+3\times l_3(t)+...+10\times l_{10}(t).$$

The constraint condition based on the fact that the total percentage of the satellites in all confidence levels is 1. $l_1(t)+l_2(t)+l_3(t)+...+l_{10}(t)=1$, we can rewrite the last equation in Eq. (1) as a differential equation with one variable $l_{10}(t)$, $\dot{l}_{10}(t) = -\lambda l_{10}(t)^2+(\lambda-\gamma)l_{10}(t)+\gamma l_{10}(t_o)$, which has analytical solution. Then, we use steady state value $\overline{l}_{10}$ to substitute $l_{10}(t)$ in the second last equation of Eq. (1), and solve it to obtain $l_9(t)$ and $\overline{l}_9$. Then we substitute $l_{10}(t)$ and $l_9(t)$ with $\overline{l}_{10}$ and $\overline{l}_9$ in the third last equation of Eq. (1), to compute $l_8(t)$ and $\overline{l}_8$. Repeat these steps for each equation in Eq. (1) until we solve all ten equations. We can use MATLAB to solve these equations for the ten confidence level OIT model and obtain the follow theorems.

Theorem 1: For a ten confidence level OIT model, assume the alignment rate $\lambda \in (0,+\infty)$, the decay rate $\gamma_2 = \gamma_3 = ...\gamma_{10} = \gamma$, and $\gamma \in (0,+\infty)$, the initial conditions $l_{10}(t_o) = \alpha$, $\alpha \in (0,1)$, and $l_9(t_o)$, $l_8(t_o)$ … $l_1(t_o) \in [0,1)$. Then, as time *t* approaches infinity, we obtain a unique equilibrium point, $\overline{l}_{10}$, $\overline{l}_9$ … $\overline{l}_1$ are given as

$$\overline{l}_{10} = \frac{(\lambda-\gamma)+\sqrt{(\lambda-\gamma)^2+4\alpha\lambda\gamma}}{2\lambda},$$

$$\overline{l}_9 = \frac{1}{2\lambda}\left(\lambda-2\lambda\overline{l}_{10}-\gamma+\sqrt{\left(\lambda\left(1-2\overline{l}_{10}\right)-\gamma\right)^2+4\lambda\gamma\left(\overline{l}_{10}-\alpha\right)}\right).$$

We use a generalized equation to represent the values of $l_8, l_7, ..., l_2$.

$$\overline{l}_{i-1} = \frac{1}{2\lambda}\begin{pmatrix}\sqrt{4\gamma\lambda\overline{l}_i+\lambda^2-4\lambda^2 l_{10i}-2\gamma\lambda+4\lambda^2 l_{10i}^2+4\gamma\lambda l_{10i}+\gamma^2} \\ +\lambda-2\lambda l_{10i}-\gamma\end{pmatrix},$$

where $l_{10i} = \overline{l}_{10}+\overline{l}_9+...+\overline{l}_i$, and $i = 9, 8, ..., 3$. And $\overline{l}_1 = 1-\left(\overline{l}_{10}+\overline{l}_9+\ldots+\overline{l}_2\right)$.

Moreover, using the value of $\overline{l}_1, \overline{l}_2, \overline{l}_2, ..., \overline{l}_{10}$ above, the steady state performance index of the ten confidence level OIT can be represented as

$$\overline{P} = \overline{l}_1 + 2\times\overline{l}_2 + 3\times\overline{l}_3 + ... + 10\times\overline{l}_{10}.$$

Theorem 2: With the same assumptions as in *Theorem 1*, the steady state performance index $\overline{P}$ is a monotonously increasing function with respect to the alignment rate λ, if we assume other parameters γ and α are arbitrarily fixed constants. $\overline{P}$ is a monotonously decreasing function with respect to γ, if we assume α and λ are arbitrarily fixed constants.

Corollary : With the same assumptions as in *Theorem 1* and *Theorem 2*, the steady state performance index $\overline{P}$ is a monotonously increasing function with respect to α, if we assume γ and λ are arbitrarily fixed constants.

Because of the limited space, we will not give the complete proof of the *Theorems and Corollary* in this paper. It should be noted that these results are only valid when time *t* is large. Because the mission life time is relatively long and we are more concerned with the steady state performance of the system, therefore, it is appropriate to use the steady state approximations with OIT model when solving the ordinary differential equations. And the above results can be expanded to the general *N* confidence level OIT model.

In the practical satellite system, the decay rate γ depends on the inherent physical properties of the attitude determination sensors and is difficult to alter once the system is deployed. Furthermore, the proportion of permanent reference node will affect the cost and complexity of the whole system and is difficult to change. However, it is feasible to increase the laser alignment rate λ by applying more effective control strategies for target searching and target aligning.

SIMULATIONS

In the following simulations, we construct a ten confidence level model to verify the results in the previous section. We assume that there are initially ten percent of permanent reference nodes which are in CL10 and all other satellites belong to CL1.

The ten confidence level satellite system parameters are $\lambda = 0,\ \gamma = 0.3/h,\ l_{10}(t_o) = l_9(t_o) = ... = l_2(t_o) = l_1(t_o) = 0.1$. The top figure in Figure 3 show the performance index versus time. Then we enabled OIT process with the alignment rate of $\lambda = 0.4/h$, other parameters remain unchanged. From the bottom figure we notice that at the steady state, the performance index increases from 1.9 (no OIT) to 8.9 (with OIT), which means that OIT process can greatly improve the average orientation accuracy of the satellite network. The performance index can be interpreted as the orientation accuracy of the whole constellation. Thus, we note that without OIT the constellation's orientation accuracy is low (1.9) but with OIT it becomes high (8.9) in steady state.

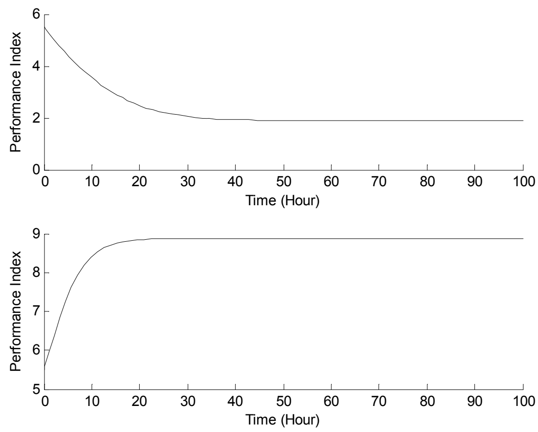

Figure 3. Top Figure: No OIT Process, Bottom Figure: With OIT Process.

The initial conditions for each confidence level are set as follows. $l_{10}(t_o) = \alpha = 0.1;\ l_9(t_o) = l_8(t_o) = ... = l_2(t_o) = 0$; and $l_1(t_o) = 0.9$. Also assume the decay rates of γ_2 to γ_{10} are identical to each other and equal to $\gamma = 0.3/\text{h}$. In the first simulation, we fix the alignment rate $\lambda = 0.5$/h, $\gamma = 0.3/\text{h}$, and $\alpha = 0.1$, then plot the change of the proportion of satellites in each confidence level during 100 hours of simulate time. The result is plotted in Figure 3. From the plot, we can compare the steady state value of the satellites in each level with the analytical result in

Theorem 1. We notice that the simulation verifies *Theorem 1*. This simulation reveals a typical OIT process in the ten confidence level satellite networks.

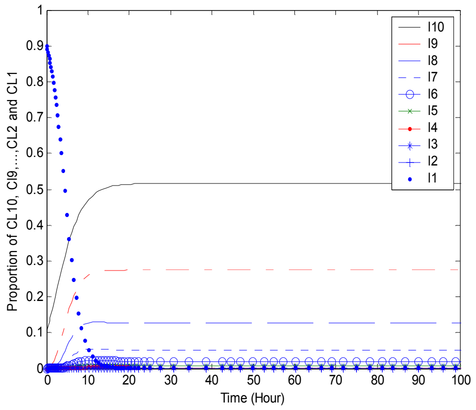

Figure 4. Proportion of Ten Confidence Levels versus Time.

PROTOTYPE IMPLEMENTATION AND FUTURE WORK

In order to verify the feasibility of the proposed laser targeting and alignment method, we designed a prototype to realize the functions of the micro-navigation sensor. The prototype consists of a GPS receiver, a solid state IMU, two lasers, two photodiodes, a DC motor controller, and a RF module. The GPS receiver and IMU provide position and orientation to the prototype, DC motor drives the prototype to rotate which simulates the laser alignment dynamics. Here we use two photodiodes as the laser detector instead of lens and CCD to reduce the complexity of building the system. The proposed method is applicable for both types of the laser detectors. The RF module broadcasts the absolute position and orientation information. All components are integrated into a cubic enclosure, as seen in Figure 5. We designed an experiment to demonstrate the OIT process. In the experiment, a laser source is fixed and its orientation information is transmitted through RF link. We consider the laser source as the reference node. The target node is the prototype we mentioned above. The motor drives the prototype to rotate until the onboard photodiodes receive the lasers. Then, according to the absolute orientation of the reference node from RF module and the relative orientation between the target and the reference node, which is determined by the laser alignment, the target node calculates its absolute orientation and reset the data from IMU. And the navigation data fusion of IMU, GPS, and lasers is achieved using a knowledge based method. Note that the experiment is designed in the laboratory environment to verify the feasibility of OIT process. Thus we use fixed lasers instead of a gimbal controller, and use one axis motor control to rotate the prototype instead of a complete three axes attitude control scheme to simplify the experimental system.

The preliminary configuration is to have numerous target satellites and a few reference satellites. The reference satellites have accurate navigation sensor and lasers, and the target satellites only have GPS and IMU as the navigation sensor. Thus the target satellite determines the navigation information by fusing data from GPS, IMU, and, if the laser alignment is available, the lasers.

We have done the experiment on ground to verify the proposed navigation data fusion method [Liu 2008]. The experiments include position tracking using only GPS, position tracking using only IMU, and position tracking using GPS/IMU data fusion. We used a knowledge based data fusion method in the experiment, we preset a “truth” path in a carefully measured area. In the first experiment, the micro-navigation sensor prototype was moved along the preset path, while the GPS position data was used to record the position of the prototype. In the second experiment, we used IMU acceleration and orientation data to calculate the position of the prototype. And in the third experiment, we fused the collected GPS and IMU data to generate a calibrated position for the prototype. The experiment results are shown in figure 6. From the figure we notice that the fused navigation data has less position error than the data from GPS or IMU alone. The results therefore demonstrate that the knowledge based GPS/IMU data fusion method is effective in reducing the GPS and IMU data.

Figure 5. Prototype for Micro-Navigation Sensor.

The implementation of the more mature system, including the CCD and lens and the experiments multiple prototypes are left as the future work. The future work also includes the implementation of the multi-stage laser alignment, two axes gimbal controller design, and the three axes satellite attitude control scheme.

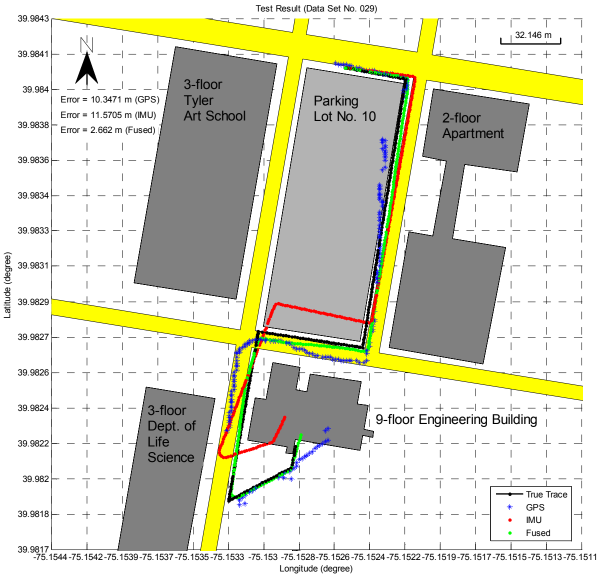

Figure 6. Comparison of GPS, IMU and Fused Data.

CONCLUSION

In this paper, we proposed a μ −NSN system for the satellite networks. In μ −NSN, satellites share and transfer absolute and relative navigation information to each other via laser alignment. We also designed the communication protocol for the micro-navigation sensor network. We discussed the orientation information transfer schedule. The key technology is in the laser targeting and control algorithms. We presented a multi-stage laser targeting design. We also designed the communication architecture for the μ −NSN system .

We analyzed the procedure of laser alignment by introducing the multiple satellite orientation information transfer. A modified epidemic model was used to model the procedure of the orientation information transfer. It is shown that the overall orientation accuracy of the constellation improves with laser alignment.

We implemented the navigation data fusion method, as the initial toward developing the μ −NSN system. We showed that knowledge based data fusion of GPS and IMU data produced better navigation information than using GPS only or the IMU only.

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