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CARTOGRAPHIC SUPPORT OF CORRELATION EXTREME NAVIGATION SYSTEMS

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Abstract

In this paper correlation extreme navigation system and its improvement is presented. Extreme navigation system is based on maps analysis, therefore accuracy of maps is very important. Magnetic field maps as the main source of information can include deviations of measurements due to variations of magnetic field. In order to minimize the influence of variations of magnetic field on magnetic field measurements magnetic observatories are used. During the process of magnetic field maps creation with a help of variation station from time to time variation station sends the request to magnetic observatory for reference data in order to correct the deviations of local magnetometers that appears due to variations of magnetic field. The problem of the given approach is that variation stations usually are located in remote areas and usage of standard Internet protocol for reference data request from observatory in some cases is impossible. The given article represents new approach for data retrieving from magnetic observatory based on usage of satellite communication.

Keywords: system CENS, magnetic field, satellite constellation, DTN protocol.

1. The problem statement and analysis of the research and publications

Nowadays in order to minimize influence of variations of magnetic field on measurements of magnetic field, variation stations and magnetic observatories are used. Variation stations that are used for magnetic field measurement use Internet protocol in order to access the reference data from magnetic observatory. Magnetic observatories reference data is very important and is used by variation stations for correction their magnetic field measurements, as far as variation stations measurements can have deviations due to variations of magnetic field. The problem of this approach is that usually variation stations and magnetic observatories are set up in remote areas in order to minimize the influence of environment on measurements of magnetic field and usage of Internet protocol in such areas is very problematic, because the network itself in the most cases is absent. The given article represents the solution for this problem.

According to the article [1] correlation extreme navigation system (CENS) is based on the idea of comparison of current realization of maps with those saved in memory (template maps) and by finding the maximal match system returns coordinates. Template maps can be of different types as an example: magnetic field maps; terrain field maps; optical field maps; thermal field maps; reflection field maps and so on. In represented experiment magnetic field maps were used. One of purposes of system CETS is determination of coordinates in the absence of GPS signals [2]: when GPS signals are absent system CENS is trying to determine the current coordinates by comparing data taken from camera or from any other sensor at given point in time with maps stored in database, by finding the match system CENS return coordinates of maps. Thus, can be seen, the accuracy of template maps is very important [3]. In given article in order to improve the accuracy of those maps the process of their creation will be modified.

Exist a set of approaches for creation of magnetic field maps. In some cases satellites are used for this purpose but resolution of those maps is not the best and expenses for equipment set up are very high. The best approach is based on usage of unmanned aerial vehicles (UAV), but given approach has its advantages and disadvantages as well. Some of them will be resolved in this article.

The disadvantages of UAV approach are the following:

- Hard and soft iron problem;
- Shifts due to temperature changes;
- Noises;
- Variation of magnetic field.

The given work proposes improvement of UAV approach for remote areas where usage of Internet protocol and as result correction of measurements with reference data taken from magnetic observatory is impossible.

The given approach proposes to integrate satellite communication support into UAV approach, to be able to access data from magnetic observatories in remote areas and perform as an result correction of magnetic field measurements.

2. "Ring Road" approach as solution of magnetic field measurements deviation problem caused by variations of magnetic field

The first possible realization of satellite communication could be the "Ring Road" approach [4] for a low-cost communications satellite network, based on the integration of LEO satellites and Delay Tolerant Networking (DTN) technologies [5]. Delay tolerant networking architecture based on scenario where only the next hop needs to be available for data to be transferred that will allow delivering service to remote areas around the world. The Ring Road system is a low-cost communications satellite network designed to provide high-latency and highly robust data interchange capability by using LEO satellites as "data mules" in a network established by Delay-Tolerant Networking.

3. Satellite constellation as solution of magnetic field measurements deviation problem caused by variations of magnetic field

The second possible solution can be presented by satellite constellation [6]. A satellite constellation is a group of satellites working in concert; low Earth orbiting satellites (LEOs) are very often deployed in satellite constellations. Many LEO satellites are used to maintain continuous coverage over an area. In comparison with "Ring Road" approach satellite constellation [7] has more complex computational logic and as a result is more preferable [8]. Examples of satellite constellations include GLONASS constellation for navigation and geodesy, the Iridium and Globalstar satellite telephony services, the Constellation and RapidEye for remote sensing, the Orbcomm messaging service, Russian elliptic orbit Molniya and Tundra constellations, the large-scale Teledesic and Skybridge broadband constellation proposals of the 1990s, and more recent systems such as O3b or the OneWeb proposal [9], etc.

OneWeb worldwide satellite broadband network has benefit from low-latency communications, so LEO satellite constellations provide an advantage over a geostationary satellite, where minimum theoretical latency from ground to satellite is about 125 milliseconds, compared to 1–4 milliseconds for a LEO satellite; a LEO [10] satellite constellation also provides more system capacity by frequency reuse across its coverage. The disadvantage of having a OneWeb satellite constellation of 700 satellites is cost. While the OneWeb satellites are physically much [11], much smaller—about 150kg (330lbs) per OneWeb satellite vs. 4000kg (9000lbs) for a geosynchronous communications satellite—it costs a lot to build 900 satellites and launch 700 satellites into space (The extra 200 satellites will be held back on Earth until they're needed [12].

From mentioned above analysis can be seen that given OneWeb approach is the best approach for data transmission in remote areas where standard Internet protocol cannot be used [13].

4. Delay Tolerant Networking protocol as realization of OneWeb technology

The Interplanetary Overlay Network (ION-DTN) software distribution is an implementation of Delay-Tolerant Networking (DTN) architecture as was described in Internet RFC 4838. It is designed to provide inexpensive insertion of DTN functionality into embedded systems such as robotic spacecraft. The reason of ION deployment in space flight mission systems is to reduce cost and risk in mission communications by simplifying the construction and operation of automated digital data communication networks spanning space links, planetary surface links, and terrestrial links.

DTN architecture is similar to the architecture of the Internet, except that it is one layer higher in the familiar ISO protocol "stack"; the DTN analog to the Internet Protocol (IP), called "Bundle Protocol" (BP), is designed to serve as an "overlay" network protocol that interconnects "internets" – including both Internet-structured networks and also data paths that utilize only space communication links as defined by the Consultative Committee for Space Data Systems (CCSDS) – in much the same way that IP interconnects "subnets" such as those built on Ethernet, SONET.

Data traversing a DTN are conveyed in DTN bundles – which are functionally similar to IP packets – between BP endpoints which are functionally analogous to sockets; multiple BP endpoints may reside on the same computer – termed a node – just as multiple sockets may reside on the same computer in the Internet. BP endpoints are identified by Universal Record Identifiers (URIs), which are ASCII text strings of form: name_of_scheme:scheme_specific_part.

As an example: dtn://topquark.caltech.de/mail.

But for space flight communications this general textual representation might impose more transmission overhead than missions can allow. Due to this reason, ION is optimized for networks of endpoints whose IDs conform more narrowly to the following scheme:
ipn:number_of_node.service_number.

The ION implementation of BP conforms fully to RFC 5050, including support for the following standard capabilities:

- Priority assignment to data flows;
- Bundle fragmentation;
- Bundle reassembly (after fragmentation);
- Status reporting;
- Custody transfer, including re-forwarding of custodial bundles due to following reasons: timeout interval expiration or failure of nominally reliable convergence-layer transmission.

5. DTN implementation principle

CGR (Contact Graph Routing protocol) as implementation of DTN technology, proposed by S. Burleigh (NASA JPL), follows a distributed approach: the next hop is determined by each DTN node on the path with a help of recomputing the best route to destination, as soon as a bundle is received. This routing procedure takes into account that a global contact plan, comprising all forthcoming contacts, is timely distributed in advance in order to enable each node to have an accurate understanding of the network. Table presents the contact plan for the sample network. Routes can thus be calculated by each node on demand, based on extensive topological knowledge of the network. This workflow is illustrated in Fig. 1 where a contact plan can be initially determined by means of orbital propagators and communication models, then distributed to the network, and finally used by the DTN nodes to calculate routes to the required destinations. CGR can dynamically respond to changes in network topology and traffic demands. An early version of CGR was flight-validated in Deep Space by NASA in 2008 and CGR has been estimated as the most studied routing solutions for space networking since then.

Table

Contact plan example

Contact №	From	To	Ini	End	Rate
1	A	B	1000	1150	1000
2	B	A	1000	1150	1000
3	B	D	1100	1200	1000
4	D	B	1100	1200	1000
5	A	C	1100	1200	1000
6	C	A	1100	1200	1000
7	A	B	1300	1400	1000
8	B	A	1300	1400	1000
9	B	D	1400	1500	1000
10	D	B	1400	1500	1000
11	C	D	1500	1600	1000
12	D	C	1500	1600	1000

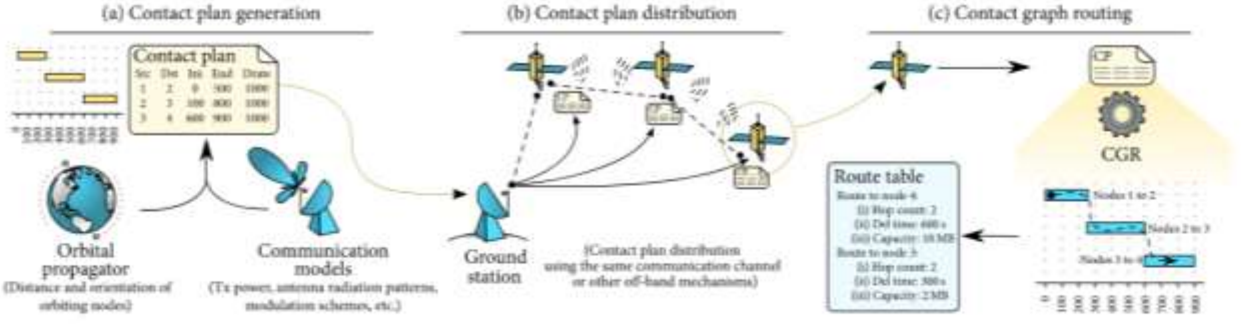

Fig. 1. Contact plan generation, distribution and utilization by CGR

CGR was documented in 2009 and later updated in 2010 as an experimental IETF Internet Draft. By the end of the same year, Segui et al. presented earliest-arrival-time as a convenient monotonically decreasing optimization metric that avoids routing loops and enables the use of standard Dijkstra's algorithm for path selection. This enhancement was then presented in the official version of CGR, included in the Interplanetary Overlay Network (ION) DTN Stack developed by the Jet Propulsion Laboratory. In 2012, Birrane et al. presented source routing to reduce CGR computations in intermediate nodes at the expense of packet header overhead. Later, in 2014, authors observed the implementation of temporal route lists as a mean to minimize CGR executions. In the same year, Bezirgiannidis et al. proposed to monitor transmission queues within CGR as they increase the earliest transmission opportunity (CGR-ETO). On the same paper, a complementary overbooking management innovation enables proactive reforwarding of bundles whose place in the outbound queue was presented by subsequent higher priority traffic. Both ETO and overbooking management are now presented in the official CGR version. Regarding congestion management, further extensions were provided as well. Most recently, in 2016, Burleigh et al. presented an opportunistic extension as a means of enlarging CGR applicability from deterministic space networks to opportunistic terrestrial networks. The latter contribution since it could, if successful; pave the way towards implementing space DTN advances on ground-based networks. At the time of this writing, CGR procedure is being formally presented as part of the Schedule-Aware Bundle Routing (SABR) procedure in a CCSDS Blue Book. All these changes have been implemented in ION software. Finally, this software becomes an important point of reference for the latest routing and forwarding mechanisms for space DTNs. The current version 3.5.0 of ION-DTN was released in September 2016 and is available as free software.

Even though the latest version of the CGR algorithm is implemented as part of the ION 3.5.0 open-source code (the CGR algorithm implemented in ION 3.5.0 includes a few parameters and procedures related to opportunistic CGR (O-CGR); O-CGR is an experimental CGR extension that also considers discovered contacts in addition to those in the contact plan; since in this work all contacts are scheduled, the probabilistic calculations are not discussed), there is no detailed description of the algorithm available yet (the CCSDS documentation is still under development). As a result, in this section, explanation of the CGR scheme is provided. The discussed algorithms are structured following their implementation in ION; however, they can be translated to more compact and elegant expressions without continue, break, and return statements.

The CGR Forward routine (Fig. 2 (a)) is called at any network node every time a new bundle B is to be forwarded. At the beginning, the algorithm checks if the local view of the topology expressed in the contact plan Cp was modified or updated since the last call (Fig. 2 (a), lines (2) and (3)). If this is true, a route list structure, holding all valid routes to each known destination, is cleared in order to force an update of the route table. Indeed, the route list Rl is derived from the local contact plan Cp. Therefore, they are only valid for certain period of time and need to be revisited by CGR for every new bundle. After that, the procedure populates a proximate nodes list Pn comprising all possible nodes that, according to the route list Rl, have a valid path towards the destination (Fig. 2 (a), lines (6)). This step is performed by the identifyProxNodes routine which is detailed in Fig. 2 (b) and discussed below. An excluded nodes list En is used in this step to avoid the consideration of administratively forbidden neighbours (e.g., unresponsive nodes) or the previous bundle sender in order to minimize route loops (Fig. 2 (a), lines (4) and (5)).

```
     input: bundle to forward B, contact plan Cp, route list Rl, excluded nodes En,
     output: proximate nodes list Pn
(1)  if Rl is empty then
(2)      Rl ← loadRouteList (B,Cp);
(3)  Pn ← ∅;
(4)  for route ∈ Rl do
(5)      if route.toTime ≤ currentTime then
(6)          continue (ignore past route)
(7)      if route.arrivalTime ≥ B.deadline then
(8)          continue (route arrives late)
(9)      if route.capacity < B.bitLenght then
(10)         continue (not enough capacity)
(11)     if route.nextHop ∈ En then
(12)         continue (next hop is excluded)
(13)     if localQueue(route.nextHop) < B.bitLength then
(14)         continue (outbound queue depleted)
(15)     for pn ∈ Pn do
(16)         if pn = route.nextHop then
(17)             if pn.arrTime > route.arrTime then
(18)                 replace pn with route.nextHop
(19)             else if pn.arrTime < route.arrTime then
(20)                 continue (previous route was better)
(21)             else if pn.hops > route.hops then
(22)                 replace pn with route.nextHop
(23)             else if pn.hops < route.hops then
(24)                 continue (previous route was better)
(25)             break
(26)     if route.nextHop ∉ Pn then
(27)         pn ← route.nextHop;
(28)         Pn ← pn;
(29) return Pn
```

(a)

```
     input: bundle to forward B, contact plan Cp, route list Rl, excluded nodes En, proximate nodes Pn
     output: bundle B enqueued in the corresponding queue
(1)  En ← ∅;
(2)  if Cp changed since last Rl calculation then
(3)      Rl ← ∅;
(4)  if B forbids return to sender then
(5)      En ← B sender node;
(6)  Pn ← identifyProxNodes (B, Cp, Rl, En);
(7)  if B is critical then
(8)      enqueue a copy of B to each node in Pn;
(9)      return
(10) set nextHop to empty;
(11) for pn ∈ Pn do
(12)     if nextHop is empty then
(13)         nextHop = pn
(14)     else if pn.arrivalTime < nextHop.arrivalTime then
(15)         nextHop = pn
(16)     else if pn.arrivalTime > nextHop.arrivalTime then
(17)         continue
(18)     else if pn.hops < nextHop.hops then
(19)         nextHop = pn
(20)     else if pn.hops > nextHop.hops then
(21)         continue
(22)     else if pn.id < nextHop.id then
(23)         nextHop = pn
(24) if nextHop is not empty then
(25)     enqueue B to nextHop;
(26)     manageOverbook (B, nextHop)
(27) else
(28)     enqueue B to limbo
(29) return
```

(b)

Fig. 2 (a, b): CGR implementation principle

The Pn list can be used to forward the bundle to the appropriate neighbors. If the bundle is critical, then bundle is cloned and enqueued to all possible neighbors in the Pn list (Fig. 2 (a), lines (7) to (9)). In case when bundle is of normal type, a single candidate node is chosen from the proximate nodes list Pn. Neighbors with best arrival times to the destination are the top priority, then those with least hop count, and finally those with a smaller node id (Fig. 2 (a), lines (11) to (23)). After, if a suitable proximate node is found, the bundle B is inserted in the corresponding outbound queue before executing the overbooking management procedure (Fig. 2 (a), lines (25) to (26)). However, in case when CGR Forward fails to find a suitable neighbor, the bundle is stored in special memory space called limbo waiting for a higher level process to either erase it or retry a new forwarding later and as a result, after the CGR routine is completed, one or more bundles might be stored in the local memory waiting for the contact with the corresponding proximate node. As should be discussed later, if, for one reason or another, the bundle is not transmitted during the expected contact, it will be removed from the queue and rerouted by this CGR routine.

The identifyProxNodes routine, depicted in Fig. 2 (b), explores existing routes to extract a proximate node list Pn. The Pn list is used by CGR routine and is formed by a set of non repeating neighbor nodes that are capable to reach the bundle destination. If the route list Rl is empty the load route list function is called in order to find all routes towards the destination of B (Fig. 2 (b), lines (1) and (2)). At this point, Rl accounts for all possible routes to the destination. Each of them should be evaluated in order to populate the proximate node list Pn. At the beginning, those routes that do not satisfy specific selection criteria are discarded (Fig. 2 (b), lines (3) to (14)). Routes with the latest transmission time (toTime) in the past, an arrival time later than the bundle deadline, a capacity less than the bundle size, and a proximate node within the excluded nodes, or that require a local outbound queue that is depleted, should be ignored. Remaining routes are then considered as suitable, and the corresponding proximate node in the Pn list should be either replaced by a better route (Fig. 2 (b), lines (15) to (24)) or directly added to the list (Fig. 2 (b), lines (26) and (27)). The replacement criterion is coherent with Fig. 2 (a): best arrival time is considered first and then route hop count, necessary route metrics such as arrival time and hop count of the best route are also stored in each proximate node data structure contained in Pn.

The routines in Fig. 2 (a) and Fig. 2 (b) are performed on a per-bundle basis. The reason behind this is that the parameters of each bundle, the local outbound queue status, and the excluded nodes list should be revised on every new forwarding in order to base the decision on an up-to-date version of the proximate nodes list Pn. These routines are considered part of a forwarding process of CGR. On another side, the route list (Rl) will need to be updated whenever the local contact plan Cl is modified. The determination of the routes is part of a routing process of CGR and is described below.

In order to find all possible routes from a source to a destination, CGR uses a contact graph expression of the contact plan. A contact graph can be presented as conceptual directed acyclic graph whose vertices correspond to contacts while the edges represent episodes of data retention at a node. Besides, two notional vertices are added: the root vertex, which is a contact from the sender to itself, and a terminal vertex, which is a contact from the destination to itself. Even though the resulting contact graph structure may seem counterintuitive, it is very convenient static representation of a time-evolving topology that can be used to run graph algorithms such as: Dijkstra’s searches. As an example, Figure 1.2 presents the contact graph. The three already discussed routes with their corresponding metrics are also included in the illustration (note that another feasible path from A to D exists through contacts 1 and 9).

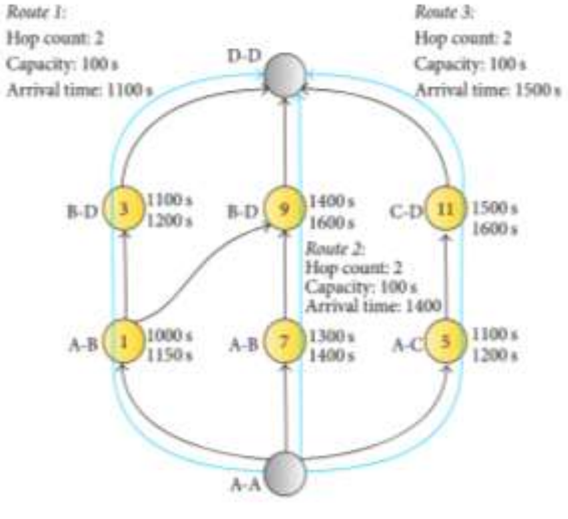

Fig. 3. Contact graph example

To find all possible routes in the contact plan, the load route list routine performs a series of Dijkstra's searches over a contact graph derived from the contact plan. Although complex algorithm, CGR is considered to be among the most mature strategies towards forwarding and routing in space DTNs.

6. Conclusions

In the given article was represented the magnetic field mesaurement deviations problem due to inability of usage magnetic observatories data for deviations correction.

The given article represented an solution for this prblem by integrating OneWeb technology into magnetic field maps cration process in order to be able to access the reference data for variation station measurements deviation correction. The detailed desription of different kinds of sattelite communications were represented; their comparison was done. The basic principle and implementation of the best approach (OneWeb) was exemined in details.

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Г.М. Бабеюнк

Картографіче забезпечення кореляційно-екстремальної навігаційної системи

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У роботі представлена система КЕНС. Дана система основана на аналізі карт, таким чином зрозуміло що їх точність є важливою для системи КЕНС. Магнітометричні карти як основне джерело інформації включають відхилення розрахунків через вплив варіацій магнітного поля для корекції динних відхилень використовуються магнітні обсерваторії. Під час процесу створення магнітометричних карт з використанням варіаційних станцій час від часу варіаційні станції виконують корекцію своїх приладів завдяки еталонним значенням магнітного поля, які дана станція отримує через Інтернет протокол з магнітної обсерваторії. Проблематика даного підходу в тому що зазвичай варіаційні станції знаходяться у віддалених зонах де використання Інтернет протоколу є неможливим. Дана робота пропоную підхід використання супутникового зв’язку як рішення даної проблеми.

Ключові слова: система КЕНС; магнітне поле; супутникові сузір’я; протокол DTN.

А.Н. Бабенюк

Картографическое обеспечение кореляционной екстремально-навигационной системы

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В работе представленна система КЕНС. Даная система основана на анализе карт, таким образом ясно, что их точность является очень важной для системы КЕНС. Магнитометрические карты как основной источник информации включают отклонения расчетов через влияние вариаций магнитного поля для коррекции дынных отклонений используются магнитные обсерватории. В процессе создания магнитометрических карт с использованием вариационных станций вариационные станции выполняют коррекцию своих приборов благодаря эталонным значением магнитного поля, т.е. вариационная станция получает через Интернет протокол данные с магнитной обсерватории. Проблематика данного подхода в том, что обычно вариационные станции находятся в отдаленных зонах где использование Интернет протокола является невозможным. Данная работа предлагаю подход использования спутниковой связи как решение данной проблемы.

Ключевые слова: система КЕНС магнитное поле; спутниковое созвездие; протокол DTN.

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