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ANALYZING SENSOR BASED POSITIONING ON THE SURFACE OF A DISTANT PLANET

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Sensors can have big advantages in the process of mapping planets and inspecting the prevailing conditions on their surfaces. We can obtain broader and more thorough pictures about the solar system bodies around us. We can not only gain new information about them, but we can observe how fast and in what way the already known data changes, and how these planets forms. For this purpose, we examined a sensor network that can withstand the environment on a planet in our solar system.

We analyzed the network's performance as well as its cost-effectiveness. The network contains some higher performance sensors, whose dedicated purpose is to collect data from the other-, (smaller) sensors, and forward this information to the satellites, which can send it back to Earth. We created the sensor network's structure in a specific way, which allows to pinpoint the location of these devices. Localization is an essential part of the mapping of any planet in the solar system.

I. INTRODUCTION

Wireless sensor networks will play a critical role in space and planet exploration in the next decades. By deploying sensors on distant planets will allow remote monitoring of non-easily accessible areas in preparation of human or robotic missions. Mobility of sensors is a vital element for a planet exploration missions due to valuable science return potential from different sites as opposed to static landers. With advancement in research and technology, many mobile systems have been developed with different geometries, sizes, and configurations. Up to the present day, very expensive and sensitive multifunctional robots with wheels or tracks were sent to other planet. However, in the future hundreds or thousands of cheap sensors can be dropped on the surface of distance orbits.

Usually not only the measured environmental features (temperature, radiation, atmosphere composition, etc.) are important, but the accurate place of the sampling, too. Therefore, the position estimation of the sensors must be solved, without complex infrastructure.

In this paper, a mobile sensor network capable for distant planetary missions was investigated. Our aim was to propose wireless sensor network architecture that can localize its elements with minimal required resources. For the position estimation process we used a recursive technique that extends the accessible coverage area using only three high performance devices with accurate positions. These devices, called supernodes, are serving as reference points for the recursive positioning of sensors, as well as gateway between the deployed sensors and satellites.

In the evaluation of the proposed model, we analyzed the performance of the positioning algorithm in an implemented simulator. In the simulator tool the surface and environmental characteristics (dunes, holes, electromagnetic storm) of a distant planet that influences the mobility and communication of mobile device was also taken into account.

This paper is organized as follows. Section II. describes the related areas of wireless sensor network deployment, data gathering methods and positioning techniques. Section III gives a detailed description of the proposed model, discusses the design goals of the architecture. The implemented tool and the simulated environment are introduced in Section IV. Section V. introduces the experimental results obtained via simulation, while the last section concludes the paper.

II. RELATED WORKS

Sensor networks are utilized in different environments, e.g., healthcare, vehicles, scientific measurements, meteorology, etc. The simple and cheap devices are able to monitor atmospherical, terrestrial, electromagnetic features and forward the collected data through the radio interface. Due to their low price and dimensions (even millimeter scale), high number of these equipment can be dispersed at the investigated area.

Sensor network deployment

The efficient deployment of sensors is very important for the successful completion of the sensing tasks. A sensor may move independently from others, but usually uniform dispersion is preferred to minimize the uncovered area. Different strategies exist to control the movement of the devices [1]. Most of these strategies [2], [3], [4] assume that the environment is sufficiently known and under control. However, in unknown or hostile environment, such as distant planets or disaster areas, sensor deployment cannot be performed manually. In these cases, the devices are scattered from great distances (e.g., airplane, space capsule), but unfortunately, the actual landing position cannot be controlled due to the existence of wind or other obstacles. Y. Zou and K. Chakrabarty [5] proposed a centralized approach, where a powerful cluster head collects the sensor location and determine the target location of the mobile sensors. However, in special deployment environment, the centralized approach is critical, because it suffers from the problem of single point failure. In case of special conditions, self-controlled methods are preferred.

Authors of [1] investigated how to maximize the sensor coverage with less time, movement distance and message complexity. The first step of their distributed self-deployment protocols is to discover the existence of coverage holes (the area not covered by any sensor) in the target area based on Voronoi diagrams [6], [7]. After discovering a coverage hole, the proposed protocols calculate the target positions of these sensors, where they should move. They introduced three movement-assisted sensor deployment protocols, VEC (VECtor-based), VOR (VORonoi-based), and Minimax based on the principle of moving sensors from densely deployed areas to sparsely deployed areas. Common feature of all the movement control protocols is that the sensors have perfect positioning and navigation capability.

Other alternative is if the mobile sensors are proceeding on a determined path [8]. In this case, the current position can be estimated based on the elapsed time and movement speed. Moreover, the future positions can be also predicted, so delivery of collected measurement data can be forwarded more efficiently. The required energy for wireless transmission depends on the distance of the devices. The relation between the energy consumption and the distance (d) of devices is d^a, where a is between 2-5 depending on the wireless propagation conditions. Energy efficient network operation can be applied, if the data transmission is triggered when the distance between the source sensor and the receiver (central) sensor is the smallest. In case of multi-hop sensor network the devices close to the central equipment will consume more energy, because the data will travel through these sensors towards the data collector equipment. Assuming a sensor network deployed on a distant planet, the central data collector device will serve as a gateway, which forwards the collected records to the satellites (as it is illustrated in Fig. 1).

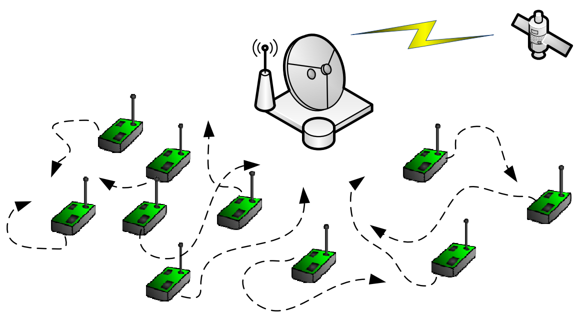

Fig. 1
Overview of a sensor network

Sensor positioning

One of the most significant challenges for mobile sensor networks is the need for localization. Sensor devices may be deployed dynamically (i.e., dropped from an aircraft or space capsule), or may continuously change position. In order to gather sensor data in a spatial context, or for proper navigation throughout a sensing region, sensor position must be known. Mobile sensors must frequently estimate their position, which takes time and energy, and consumes other resources needed by the sensing application. Therefore, localization schemes that provide high accuracy positioning information in wireless sensor networks cannot be employed by mobile sensors [9].

Different type of position estimation method exists, but all of them are based on measurement of different radio signal propagation feature.

While receiving a radio signal, some of its properties, such as arrival time, signal strength, and direction, are captured by the receivers. In second phase certain signal parameters, such as TOA (Time of Arrival), TDOA (Time difference of Arrival), RSS (Received Signal Strength), and AOA (Angle of Arrival) are extracted from the captured values. The three most popular categories of methods for position estimation are time based; angle based and received signal strength based method.

With TOA [10], the distance between the transmitting node and the receiving node is deduced from the transmission time delay and the corresponding speed of signal. The main drawback of this approach is that it is difficult to precisely record the arrival time of radio signals, since they travel close to the speed of light.

TDOA localization [11] improves upon the TOA approach by eliminating the need to know when the signal was transmitted. Several time-synchronized nodes receive a signal, and look at the difference in arrival times.

The AOA method [12] determines the angular separation between two beacons, or a single beacon and a fixed axis. This method requires special antennas.

Using RSS based technique [13] the distance is measured based on the attenuation introduced by the propagation of the signal from the transmitting node to the receiving node. An empirical mathematical model is used to calculate the distance according to signal propagation.

As the final step, the calculation of the coordinates is done using triangulation (AOA) or trilateration (TOA, TDOA, RSS) [9].

III. PROPOSED MODEL

More questions are raised regarding monitoring the environment of a distant planet. During the sensor network planning process the monitored data types, network topology, sensor movement strategy must be defined.

Measurable data on a planet

On the surface of a planet different type of data can be monitored and forwarded. We must define how important the measured data are. In case of water discovery or soil pattern monitoring it is not a problem if the collected data reach the command center on the Earth later, they remain valid. However, if temperature is measured, it is important to arrive in time, because the collected data will lose actuality. In addition, we must define that the measuring process is periodic, continual or event controlled. In our model we chose a sensor network, assuming that the data are valid for period of time and the measurement is periodic.

Satellite system

A satellite system enables us to forward the measured data to the communication station. If more satellites are used, permanent coverage can be ensured, but on the other hand the deployed network will be too expensive or even unrealizable. Therefore, we suppose to use a slim satellite system keeping the number of satellites as low as possible in our model.

Sensors movement

The sensors are able to move and make measurement at different positions. In order to model the movement of the sensor equipment, we used both random and fixed path motion. The sensors get a random motion direction first, then a protecting zone border is appointed, which determines the limit of the *y* coordinate displacement. Due to the iterative positioning technique that is used to estimate the coordinates of the equipment, the sensors must stay in a bunch and do not come away from each other. If some sensors reach the border limit, their angle must be changed. During the angle adjustment, *y* coordinate of the motion changes, so the chance of leaving the lane will be smaller. In case of crossing the lane border, the connection will be probably lost with the sensor, as it is shown in Fig. 2. The left original spots sign the starting point of sensors. The seeded spots sign more power sensors that are able to communicate with satellites and determinate their accurate position using GPS. In Fig. 2 we can follow the movement of a sensor. The first single spot (step 2) shows the position after the first step. Here the sensor reaches the protecting zone border, so its *y* coordinate changes (it will become -*y*) and begins to move to a new direction. The *x* coordinate is not modified during the movement, so the sensors will move until reaching the line of point *D*. Using high number of sensors, we can ensure that measurements will be performed uniformly on the determined territory of the lane from the starting line to the end line.

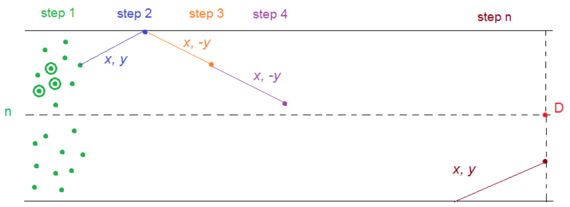

Fig. 2
Movement of sensors in our model

Supersensors in the network

In our model, we used some special sensors, named supersensors. The supersensors collect the data from the other sensors and forward to the Earth via satellites. Their actuation is more expensive because the communication with satellites needs more energy that must be produced using bigger solar cells, compared to other regular sensors. We assume that these sensors are able to precisely determinate their own position (e.g. through GPS) and serve base point for the iterative position estimation process of regular sensors. The supersensors move in group with the other simpler measuring sensors too, so they ensure to be at service, if there is data that must be forwarded.

Sensor positioning

Due to the lack of the necessary infrastructure, we do not use GNSS-based *(Global Navigation Satellite System)* navigation. Instead of this, we use the way of triangulation as it is shown in Fig. 3. Knowing the position of three sensors, we are able to calculate the position of a fourth sensor, if this sensor is visible for the three others.

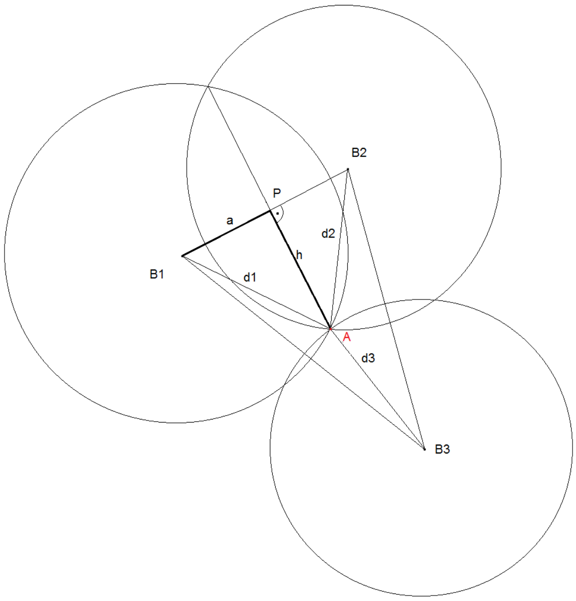

Fig. 3
Calculating the position of sensor *A* using triangulation method

The *B1*, *B2* and *B3* points are the known position sensors, sensor *A* (in the middle) has the unknown position. We want to calculate its position. For this, we use circle engraving. If the cover of sensors *B1*, *B2* and *B3* are bigger than the distance from sensor *A*, then the way is adaptable. Circles, with *d1*, *d2* and *d3* radius and *B1*, *B2* and *B3* centre, define the position of *A*. In this case, the *B1*, *B2* and *B3* are reference points. (The reference point is the position of a sensor, which assists to the positioning algorithm.) After determining the position of *A* sensor *A*, it will become a reference point as well.

Using this technique recursively and assuming that there are no lost sensors, all of the sensor bunch will be known. If there are some lost sensors, then the determination process will be harder as it is explained in our simulations.

At the beginning of our algorithm, the firs reference points are the supersensor. These position always are known, because they can communicate with the satellites.

We use the following formulas for the calculation.

$$A(x) = p(x) \pm \frac{h(y2 - y1)}{dist(B1, B2)} \quad (1)$$

$$A(y) = p(y) \pm \frac{h(x2 - x1)}{dist(B1, B2)} \quad (2)$$

where *x*, *y* are the coordinates of sensors, *p(x)* and *p(y)* are the coordinates of point *P*, and function *dist*(*B*1,*B*2) returns the distance between *B*1 and *B*2.

Sensor communication

The measuring sensors can communicate with each other (multi-hop network) forwarding the monitored data sensor to sensor. The other solution is if the communication works only between a sensor and supersensor (single-hop network). In the first case, the data can reach to the supersensors with more steps, while in the second case the sensors must wait until they arrive within the range of a supersensor. In our model the supersensors move in group with the regular sensors, so we choose the second case due to its simplicity.

Crater, dune and dust storm

In reality there are number of physical factors, which typify the real conditions on the surface of planet. In this paper we have taken crater, dune and the dust storm into account. In case of crater or dune, we examined the superficial disparity. We examined how the sensors move on a planet surface where holes or hills are. In case of dust storm, the signal propagation characteristics deteriorate, leading to connection lost between the sensors. If the received signal strength decreases under the sensitivity threshold, the positioning will not work. Without positioning the chance of group brake up will be bigger because the sensors can overstep the zone border. After the storm, the sensors must renew the relation with each other; however it can be hard, because some of the sensors will be lost.

IV. SIMULATION TOOL

In order to analyze the introduced sensor network architecture and evaluate its operation a simulator tool was implemented in C#. The input of the tool is a surface map that describes the superficial characteristics, number of sensors, movement lane, positioning error, storm period, etc.

Error propagation

While applying the positioning algorithm, different errors will occurred, e.g., variant measurement and rounding (calculations) errors. This means that the calculated coordinates will not perfectly match the real coordinates. If we use these dissimilar values in further positioning calculations, than the discrepancy will be bigger. By more-stairs positioning, this is the phenomenon of error piling. It cause significant problem, if sensors could be able to communicate according to their real positions, but the range of sensors is so big according the calculated values, that they misbelieve their communication ability. In a real environment, sensor does not come away by the bunch, but it perceives contrariwise, so the measured data are not transferred.

We demonstrated this phenomenon as follows. We added a random generated number to the calculated x, y values by the positioning algorithm. Limits of this value are in the [0, $error_{max}$], where parameter $error_{max}$ is the maximum value of error. We have added error to the calculated value and we will take into account this value later. With this, the discrepancy will be better from the real coordinate by the calculation of further steps. The value of error will be added to coordinates function of the positioning algorithm.

Using of maps

We used two different maps in our simulation program, a relief map and a surface chart. The relief map shows surface of the given planet. The simulation program defines aboveground altitudinal values from RGB (red, green, blue) color-code. We use these values by positioning and moving of sensors. The surface chart shows the different soil types of the planet. Two types were used in our simulations, gravel-covered ground and sandy soil. The soil type affects the speed of the sensors, lowers it with varying degrees. In this type of map, the program reads data from RGB color-codes also, and makes allowance for counting.

Determining routes

Determining the route of a sensor was a challenging problem. As shown in Fig. 4, a sensor wants to go from the candidate start point *A* to the candidate target point *B*. Since pixel-based maps are used, the related route has to be defined in pixels. Because we can calculate only the centers of pixels, that pixels fall into the route, which are concerned by bee-line between the two points.

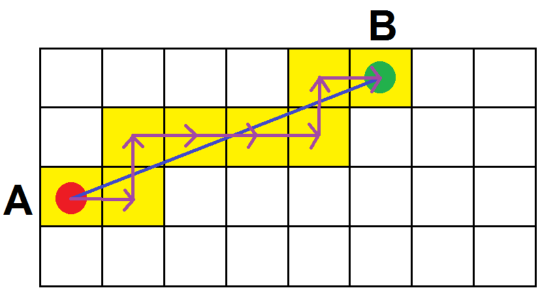

Fig. 4
Determining routes in our pixel-based map

Vertical displacement

In the simulation, the sensors do not move only on smooth, horizontal surface but confront with dunes and craters. So we use for the aboveground altitudinal values by their move. Unequivocally, the sensors move faster on downhill ground, and slower on upward ground. We initiated a gradient angle, which describes that gradient, the sensor move further in the next step. This angle affects the speed of advance considerably. The following rule was defined: if gradient angle is over 45° or below -45°, the sensor will be unable to move and it will stop.

V. SIMULATION RESULTS

Variation of percent value of calculable position sensors in function of number of sensors

One of the investigated problems was the following. We have different numbers of sensors which positions are calculated from position of three sensors. How does the change of number of sensors affect our calculations?

How does the success of position depend on number of all sensors?

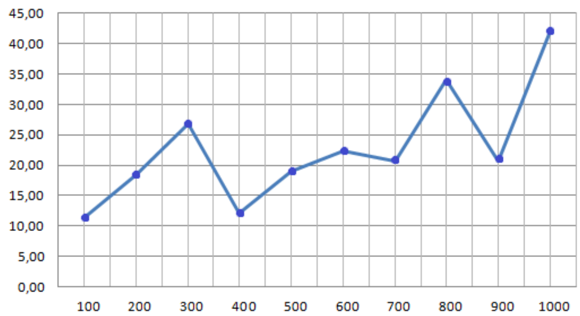

Fig. 5
Variation of percent value of calculable position sensors as function of number of sensors
Horizontally the number of sensors, vertically the percent value of calculable position sensors

For the demonstration, we represented the calculable sensor positions in percent value. As shown in Fig. 5, the values jump although, but they throve on the whole. Therefore, more sensors are in the sensor network, more position of sensor is calculable. It is important to remark in this case, that the success of position does not depend on calculation by supersensor or by reference sensor.

Variation of number of lagging sensors in function of term of dust storm

Another interesting question is how a dust storm affects the positioning. We were especially interested in the change of sensor, where there is a dust storm.

How does number of lagging sensors change by the alteration of term of dust storm. The breakaway can happen, because there is not communication between the sensors during dust storm. So there can be some sensors, which stray outside the safety bound without perception. There are not three so sensor out of bound most probably, that the range of available.

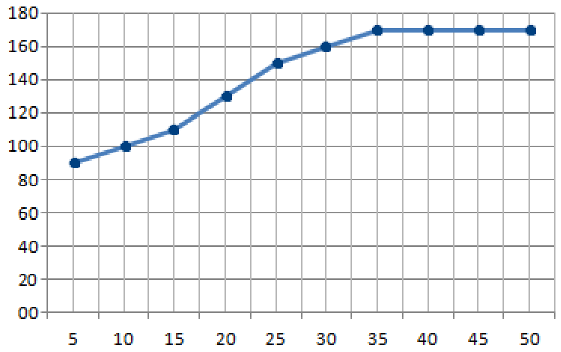

Fig. 6
Variation of percent value of calculable position sensors as function of number of sensors.
Horizontally the time of the durst storm (in sec), vertically the number of lost sensors is represented.

Our results are shown in Fig. 6. If the dust storm continues longer, more sensors will come off from the bunch. At a given point, there will be no communication between sensors, so they will not be able to determine their position any more. They overlook that, they arrive outside the specified band or can come off from the bunch and so move away into the bad way. This result that, more sensors can come away. As it can be seen, the result stagnate after a given value (~33s), namely all sensor came away from the bunch here (except supersensors) and almost, the whole network is lost by that long-term dust storm.

Variation of average error in function of reach

The main questions investigated are the followings: How does average error on sensors change bit by bit in case if change of reach of sensors. Our results are shown in Fig. 7.

This error value is an integrated value the sensors bit by bit separately, where the error shows the difference of real and calculated value. In case of this, we changed the reach of sensors also, value of that distance, which the sensors can see each other. We investigated that, how does an average error value change depend on this. We average this error values separately for the sensors, then we took the average of values bit by bit. With this method, we were able to represent the results intuitively.

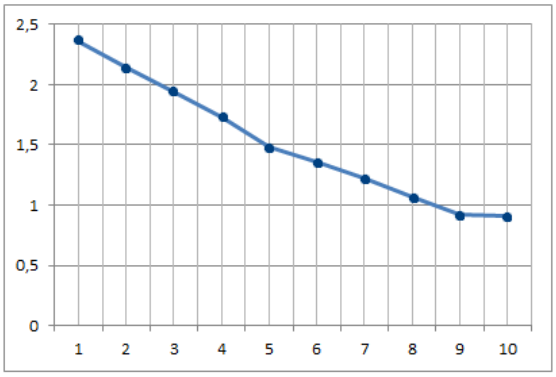

Fig. 7
Variation of average error in function of reach
Horizontally the reach of sensors (in m), vertically the average error (in m)

If the covered area of sensors has a bigger value, then the average error is lower, because more sensor's position can be calculated by the way of triangulation. This value will be more accurate, if we will have fewer errors. We can calculate position of other sensors further from this. This means the error accumulate in less steps, the average error will be smaller. If the value of distance is smaller, the value of average will be bigger, because we can calculate the position of sensor more steps, the error accumulate in more steps, too. A stagnant value is discernible by a given reach (~9m). So if the reach is big enough, than the average value of error stop on a constants value. If the reach is so big, we can define the position of all sensors in one step, the supersensors reach the all other sensors, then we must calculate a minimal error in this step just.

V. CONCLUSION

In our work, we dealt with a sensor based network on the surface of a distant planet. We developed a network model or such a network, and implemented a simulator software to evaluate the network. We analyzed the performance of the positioning algorithm, and studied the network's performance as well as its cost-effectiveness. As a further work, we plan to extend our model and to continue the development of the simulator program.

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