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ENERGY EFFICIENCY OF MULTI-HOP SENSOR NETWORK ON THE SURFACE OF SOLAR SYSTEM PLANET

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Space exploration plays an important role to understand the behavior of our planet and universe. Engineers are developing different scientific equipment and devices, which are used in the space research and space exploration. There are several solutions to discover and continuously investigate a selected area on a surface of a Solar System body, which are based on expensive devices and sometimes on human monitoring. Instead of complex and expensive robots, we propose to deploy high number of cheap mobile sensor devices on the orbital planet surface to make the exploration more effective. These sensors form a multi-hop network and communicate with each other offering many challenges from communications point of view.

Our aim was to examine how to model, follow and control the movement of the sensor network in this special environment without losing the radio connection with any sensor. Moreover, we analyzed the effects of variant aboveground events (e.g., dust storm) on the communication in this network. The supposed sensors can make different measurements and take photos. In order to extend the examined surface, it is necessary to make the sensors movement possible. The knowledge of measurements' position is necessary for the data processing, in order to get accurate image for the surface of planet. Due to the lack of a global navigation satellite system, the sensors have to follow the movements and estimate the position of the other devices. We proposed extended positioning algorithms based on the triangulation method using simulation methods. However, the positioning ability of the algorithm is not effective if it includes unrealistic large energy consumption. This is why the examination of energy efficiency was in focus in our current work. Our aim was to get valid image about the performance and energy consumption of the developed algorithms. In the developed simulation program, we were able to define the main parameters of the sensor network in order to make the surface exploration more effective.

I. INTRODUCTION

Nowadays, high levels of technical developments appear in daily life and in more and more scientific areas. One of most important area is the space exploration. At first, we must map the given surface for safe and effective using of the newer and more expensive measurement devices. We suggest to use sensor networks for exploring the surface of solar system bodies.

The sensors are small detecting devices, which are applicable on several areas, e.g., medicine, safety system, development of car parks. Since they are cheap devices, they can be used in large numbers to increase the efficiency.

A sensor network can be used on surface of distant planet for different measurement and exploration. In this work, we examined a possible sensor network in area of Mars, including some surface factors (sandstorm, craters, dunes), which have influencing effect on positioning and energy management of network elements. Sensors are able to perform different measurements (e.g., radiation detection, atmospheric measurement, magnetic field measurement), visual recording. In addition, there are some higher power sensor, which can communicate with control center on the Earth and forward the common data. The general setup is illustrated in Fig.1.

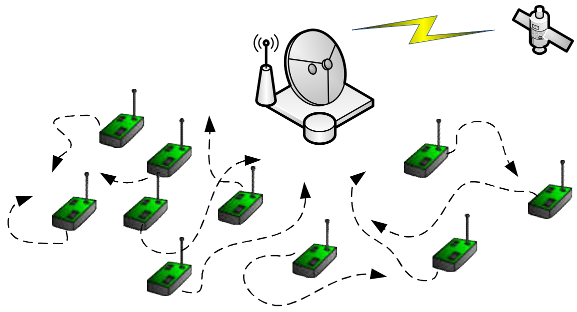

Fig. 1
General overview of a monitoring sensor network

To perform these measurements, the position of the sensors needs to be determined without using any satellite based positioning and navigation system. Positioning facility of sensors solves this problem. There is an error in distance estimates of sensors due to influential ground features and signal attenuation. The estimation error is low in the beginning, but in case of multi-hop positioning its value increases preventing communication connections and resulting data loss. In our work, energy efficiency of sensor network is in the focus. Since sensors are simple devices, they do not have large battery or solar unit, in addition, resource supply is difficult task depending on the location on surface of distant planet. The energy consumption behavior of the sensor network must be kept on minimum.

We developed a C++ program for simulation, which models the behavior of a sensor network, its positioning method on the area of Mars and energy comsumption efficiency. The goal of our work was investigate the potential energy efficiency of sensor network application by a complex simulation tool, which is able to take the special environmental conditions into consideration.

II. IMPORTANCE OF SENSOR NETWORKS

Sensor networks are becoming part of our lives, deployed in different environments, e.g. smart homes, healthcare, vehicles, scientific measurements, meteorology, etc. Researchers are sending sensor devices to explore and analyze the bottom of oceans [1] or even active volcanos [2]. The simple and cheap devices are able to monitor atmospherical, terrestrial, electromagnetic features and forward the collected data through their radio interface. Due to their low price and dimensions (even millimeter scale), high number of these equipment can be dispersed at the investigated area. Utilizing mass of sensor devices for distant planet exploration can be very promising.

In order to maximize the efficiency of sensors, the optimal deployment is necessary 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, while in some cases dense sensor coverage is preferred in some parts of the territory and sparse density in other parts. Different strategies exist to control the movement of the devices, but most of these strategies [3], [4], [5] 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), hence the actual landing position cannot be controlled due to the existence of wind or other obstacles. In paper [6] centralized approach was proposed, 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 can suffer from single point failure. In case of special conditions self-controlled methods are preferred to prevent inapplicability of the whole sensor networks in case of device failures. A sensor be also out of service if the battery level became too low.

Wang et al. [7] investigated how to maximize the sensor coverage in short time, with low 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 [8]. After discovering an uncovered area, the proposed protocols calculate the target positions, where the sensor should move. They introduced three movement-assisted sensor deployment protocols based on the principle of moving sensors from densely deployed areas to sparsely deployed territories. Common feature of all the movement control protocols is that the sensors have perfect positioning and navigation capability.

One of the most significant challenges for mobile sensor networks is the need for accurate position estimation. Sensor devices may be deployed randomly (e.g., dropped from space capsule) and change their position continuously. Accurate sensor position estimation is essential from the data gathering in a spatial context and device navigation point of view. Mobile sensors must frequently determine their position, which takes time and energy, and consumes other resources needed by the sensing application. Most of the position estimation methods 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. Based on these values, the three most popular categories of position estimation methods are time based; angle based and received signal strength based solutions. Each solution has its benefits and drawbacks. In case of TOA [9] and TDOA [10], it is difficult to precisely record the arrival time of radio signals and synchronize the transmitter and receiver clocks, however the accuracy is relatively high. The AOA method [11] determines the angular separation between two beacons, or a single beacon and a fixed axis. This method requires special antennas. Using RSS based technique [12], the distance between the transmitter node and the receiver node is estimated based on the radio signal attenuation caused by the propagation of the signal. Empirical mathematical models are 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) [13]. All the positioning systems assume that reference points exist is the network with precisely known coordinates. However, recursive positioning [14], [15] is an alternative solution that can increase system coverage iteratively, as nodes with newly estimated positions join the reference set. In hostile environment, where only few high power centralized device can be deployed, recursive positioning can extend the sensor network coverage. Recursive positioning method has several positive features, e.g., it is a good solution for sensor nodes with limited range capabilities and efficiently counteracts the sparse anchor node problem. However, it has critical design issues as well, e.g., positioning error may accumulate along the iterative process. In our model, proposed for monitoring distant planets with wireless sensors, utilizes the benefits of this method.

All of the positioning solutions are based on radio signal broadcasts that have energy rated issues, too. The required energy for wireless transmission depends on the distance of the devices. According to [16] the relation between the energy consumption and the transmitter-receiver distance (d) can be estimated as d^a, where a is between 2-5 depending on the wireless propagation conditions. Energy consumption of the wireless communications can be reduced, if the data transmission is triggered when the distance between the source sensor and the receiver device is the smallest.

In mobile devices, mechanical actuation has much higher power consumption than communication, sensing and computation [17]. Therefore, energy efficient movement is very important for mobile nodes to increase their lifetime when energy recharge is difficult. Energy efficient motion planning has been studied by in several papers [18], [19] in order to find the most energy efficient path from a source point to a destination point.

Reduced energy level can lead to communication failures that also impact the positioning accuracy, especially in case of recursive positioning solution. An interesting aspect is how the accuracy vs. energy consumption trade-off changes.

Wireless sensor networks will play a pivotal role in space and planet explorations. In most space missions, the localization of each node is essential in order to know where each measurement has been made. Without energy, neither communications nor positioning is possible. Depending on the mission and objectives, energy could be either harvested from the environment or/and stored in batteries, but the available amount of energy is limited in both cases [20]. Therefore, analyzing the accuracy of positioning solutions (e.g. recursive positioning) from the energy management point of view is an important task.

III. ANALYZING ENERGY EFFICIENCY

Energy consumption

The state diagram of energy consumption of sensors is shown in Fig 2. The movement, communication, measurements and measurement processing entail energy loss. These activities will be done only if the energy level of given sensor is high enough. For example, if the energy level does not reach the given limit for the movement, the sensor will stay in the state of standing.

At first, the capacity of sensor accumulator has to be defined. Since we do not have working sensor networks so far in space environment, we used the accumulator size of a small remote-controlled car in our calculations. The small remote-controlled car is more complicated than a simple sensor, but its base functions (movement communication with remote controller) give starting point for estimating the capacity. We used the values of an average small remote-controlled car [21] with 9.6 [V] and 2 [Ah] accumulator size, so the maximum capacity of sensors is 69120 [J]. All the simulations were made with these values, except where the accumulator capacity was the examined parameter.

To estimate the energy need of sensors in space, we evaluated the energy requirement of recording with a digital camera [22] as a reference. Its maximum accumulator capacity is 8.64 [Wh]. 1100 pictures can be taken with one charging, so taking one picture needs ~0.00785 [Wh], 28.27 [J]. Our time-controlled simulation program works with 10 [s] timeslots. For an easier calculations, we used this value for energy consumption of additional measurements and movements.

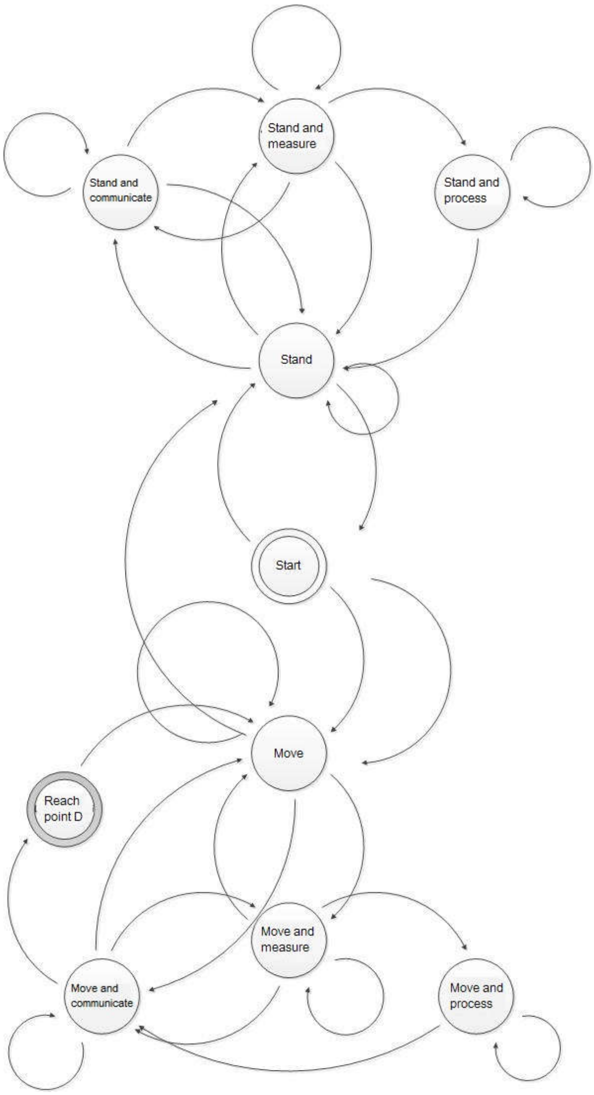

Fig2. State diagram of sensors moving and communicating on the surface of a Solar System body

The communication between sensors demands negligible amount of energy compared to measurement and movement. The necessary amount of energy is shown within 10 [s] timeslot is presented in Table 1.

Operation	Default energy need
Visual recording	28.27 [J]
Radiation detection	28.27 [J]
Atmospheric measurements	
Magnetic field measurements	
Communication	
Movement	28.27 [J]

Table 1 Parameters of energy needs within a 10 s time window

Energy revenue

In order to ensure that the sensors are useable in a long term interval, external resources are needed, which are able to reload the accumulators. In case of sensors with solar cell, this external resource is the Sun. We used the following equation

$$W[J] = t \cdot \mu \cdot E_n \cdot A \quad (1)$$

where,

μ is the solar cell efficiency (between 6% and 14%),

E_n is the energy of sunlight, (we used 600 [W/m^2]) ,

A is the surface of solar cell (~100 [cm^2]),

t is the using time (due to the timeslot value used in our simulation program is 10 [s])

These values are summarized in Table 2.

Name of parameters used in the simulation	Default values used in the simulation
Efficiency	6-14%
Energy of sunlight	600 [W/m^2]
Surface of solar cell	100 [cm^2]
Using timestamp	10 [s]

Table2

The used parameters of energy revenue

IV. SIMULATION RESULTS

Our goal was to show how an energy efficient analyses of a sensor network can be performed in a space-based environment and what types of key questions should be identified and answered.

In our simulation, we looked for different influencing factors which react to energy consumption. With their help, we can determine different base connections of energy consumption. In the following simulation diagrams, we marked the confidence intervals with 95% level.

In Fig. 3, a part of the average amount of energy change next to 69120 [J] accumulator capacity is illustrated. We chose such a time interval where the decreasing energy level prohibit the sensors to perform operations at a given point. After this point, energy level of sensors stay on a given value (~20 [J]) with more of less difference. Since the energy level of sensors does not reach values of measurement and movement detailed in Table 1, energy consumption was not seen. In a real environment, the energy reserve does not stagnate after this point, instead increases with the help of solar cell. But this is happening so slow comparing to the time window of the simulations, that it does not appears in the diagram.

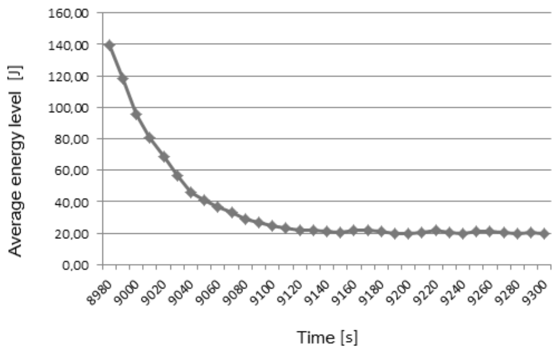

Fig. 3. Change of average energy level of sensors in function time with 69120 [J] accumulator capacity

Based on these results, a period of time can be defined which shows how much time is needed for full loaded accumulators to decrease to the level where sensors are not be able to movement or measurement. In case of 69120 [J] accumulator, this value is ~9080 [s].

Another time period can be defined which signs the time of sensors are in moving or measuring state. In an ideal case, there are not influencing factor of loading, (e.g., dust storm which does not enable to have access of sunlight), the efficiency of solar cell is high enough and there are no operations which result energy loss. Using Equation (1), we can calculate the energy income (6 [J]) in case of 10% solar cell efficiency. Assuming simple proportion, the necessary 84.72 [J] will be available in 1414.2 [s]. (As it can be concluded by the calculated data, Fig. 3 does not illustrate an ideal case.)

These two parts of time determines a measurement period, which defines how much time is available for the sensor network to stay in a suitable energy level state in case of given parameters. In order to make this time shorter, we have to decrease the energy consumption or increase the surface of solar cell.

Every sensor starts its movement from a common start point and they have to reach a predefined endpoint or target point. We examined how much time is necessary to reach the target point of the simulation. These analyses were made in the function of accumulator capacity. The results are shown in Fig. 4.

The arrival time decreases in large steps to a given accumulator size (~59120 [J]). After this value, small steps decrease trend is observed, but after 99120 [J], the values are stagnating. Its reason is that the sensors reached the target point and they are not moving any more. Our results show that it is not recommended to choose larger value than 99120 [J] for accumulator capacity.

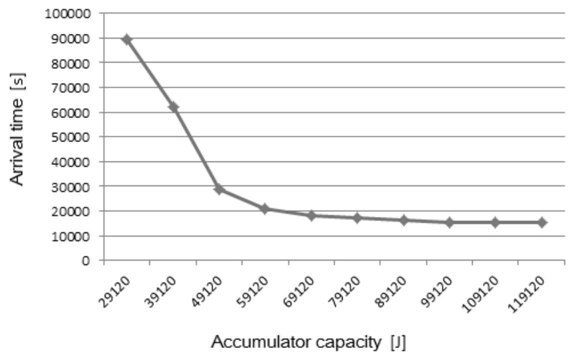

Fig. 4. Arrival time in function of the accumulator capacity

We got an upper estimate for accumulator capacity, but we were interested in the minimal value as well. Thus, we examined the change of positioning error value in function of accumulator capacity. Positioning error is the difference between real coordinates and estimated coordinates by the selected positioning method. The results are shown in Fig. 5.

Large error value is typical between 29120 [J] and 59120 [J], but after 59120 [J], smaller (near zero) values are seen. The reason behind this is that sensors discharge sooner in case of smaller accumulator capacity, and this energy level is not enough for communication.

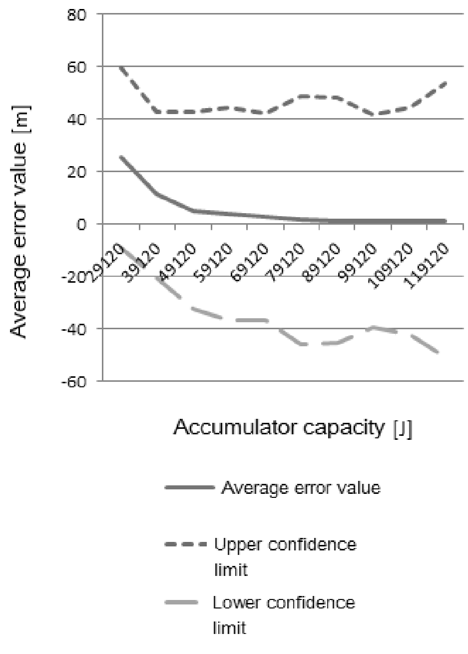

Fig. 5. Change of average error value in function of accumulator capacity

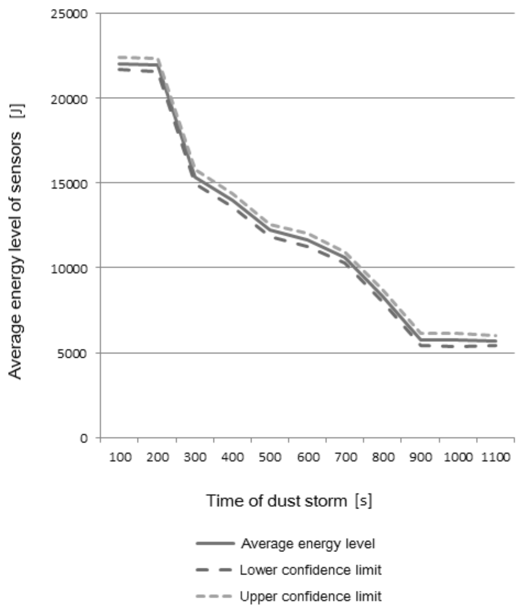

Fig. 6. Average energy level of sensors in function of dust storm time

So the sensors, having smaller error, do not available with bigger chance. This indicates that the accumulator capacity should be larger than 59120 [J] next to the given parameters. However, a state with smaller steepness is observed, that is mean the larger capacity values cannot repair the errors value significantly. So we can conclude that larger than 89120 [J] value is not worth.

Dust storm has influencing effect on the energy consumption of sensor network. In case of dust storm, these sensors are not able to communicate with each other, so the positioning will be impossible in this time. But their movement continue, so they can move away from each other. Storm dust have another important effect, the solar cells does not charging, this unmakes the energy efficiency.

The related simulation results are shown in Fig. 6. A decreasing trend can be observed. The larger storm term results smaller average energy level. This is expected, because deficit of the solar cell eventuate significant energy loss.

V. CONCLUSION

In the future, sensor networks can play an important role in discovering the surface of different solar system bodies. In this work, we utilized the concept of a sensor network which consists of large number of simple sensors moving on the surface of Mars. We developed a complex framework to analyse the movement, positioning and communication in such a network. In most space missions, the localization of each node is essential in order to know where each measurement has been made. But without energy, no communications nor positioning is possible. In this work, our goal was to show how an energy efficient analyses of a sensor network can be performed in a space-based environment and what types of key questions should be identified and answered.

REFERENCES

[1] K. Liu et al., "OceanSense: Monitoring the Sea with Wireless Sensor Networks", Mobile Computing and Communications Review, vol. 14, no. 2, pp.7–9, 2010

[2] G. Werner-Allen, K. Lorincz, et al., "Deploying a wireless sensor network on an active volcano," IEEE Internet Computing, vol. 10, no. 2, pp. 18–25, 2006.

[3] S. Dhillon, K. Chakrabarty and S. Iyengar, "Sensor placement for grid coverage under imprecise detections," Proc.International Conference on Information Fusion, 2002.

[4] S. Meguerdichian, F. Koushanfar, M. Potkonjak and M. B. Srivastav, "Coverage Problems in Wireless Ad-hoc Sensor Network," IEEE INFOCOM'01, Apr. 2001.

[5] S. Meguerdichian , F. Koushanfar, G. Qu and M. Potkonjak, "Exposure in Wireless Ad-Hoc Sensor Networks," Mobicom, 2001.

[6] Y. Zou and K. Chakrabarty, "Sensor deployment and target localization based on virtual forces," INFOCOM, 2003.

[7] G. Wang, G. Cao, and T. Porta, "Movement-assisted sensor deployment", in Proceedings of. IEEE INFOCOM'04, Hong Kong, 2004.

[8] D. Du and F. Hwang S. Fortune, "Voronoi diagrams and Delaunay triangulations," Euclidean Geometry and Computers, 1992

[9] N.B. Priyantha, H. Balakrishnan, E.D. Demaine and S. Teller, "Mobile-assisted localization in wireless sensor networks". In: Proc. of the IEEE 24th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM), vol. 1, 2005

[10] B. Kusy, J. Sallai, G. Balogh, A. Ledeczi, V. Protopopescu, J. Tolliver, F. DeNap and M. Parang, M., "Radio interferometric tracking of mobile wireless nodes". In: Proc. of MobiSys, 2007

[11] D. Niculescu and B. Nath, "Ad hoc positioning system (APS) using AOA". In: Proc. of the Twenty-Second Annual Joint Conference of the IEEE Computer and Communications Societies, INFOCOM, 2003

[12] H. Lee, M. Wicke, B. Kusy and L. Guibas, "Localization of mobile users using trajectory

matching". In: MELT 2008: Proc. of the first ACM international workshop on Mobile entity localization and tracking in GPS-less environments, pp. 123–128, 2008

[13] I. Amundson and X. D. Koutsoukos, "A Survey on Localization for Mobile Wireless Sensor Networks", R. Fuller and X.D. Koutsoukos (Eds.): MELT 2009, LNCS 5801, pp. 235–254, 2009,

[14] J. Albowicz, A. Chen, and L. Zhang, "Recursive position estimation in sensor networks". In IEEE Int. Conf. on Network Protocols, pp. 35–41, Nov 2001.

[15] A. Szeile, A. Huszak and L. Bacsardi, "Advanced Sensor Based Positioning and Monitoring System", Global Space Application Conference (GLAC 2014), Paris, France, 2-4 Jun 2014.

[16] Z. Butler and D. Rus, "Event-based Motion Control for Mobile Sensor Networks", IEEE Pervasive Computing, Vol. 2, No. 4, pp. 34–42, Oct.-Nov. 2003.

[17] K. Dantu, M. Rahimi, H. Shah, S. Babel, A. Dhariwal and G. S. Sukhatme, "Robomote: Enabling Mobility in Sensor Network". CRES-04-006 CRES Tech Report.

[18] Z. Sun and J. Reif, "On Energy-minimizing Paths on Terrains for a Mobile Robot". IEEE International Conference on Robotics and Automation (ICRA), Sept. 14-19 2003

[19] G. Wang, M. J. Irwin, P. Berman, H. Fu, and T. F. La Porta, "Optimizing sensor movement planning for energy efficiency," in Proc. International Symp. Low Power Electron. Design (IPSLED), San Francisco, CA, pp. 215-220., Aug. 2005,

[20] J. Hayden, J.R. Agre, L.P. Clare and T.Y. Yan, "Advanced communication and networking technologies for Mars exploration" 6. Vol. 210975. NASA Glenn Research Center, 2001.

[21] Website of Tenergy, http://www.tenergy.com (Last visit: September 8, 2015)

[22] Website of Canon, http://www.canon.hu (Last visit: September 8, 2015)