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Description	

Design Automation of One-Time-Use Leaping Mechanism for Sensor Node Relocation

Gabseong Lee, Geunho Lee, Yasuhiro Nishimura, Nak Young Chong, and Dong-Hoon Choi

***Abstract*— This paper proposes a design automation method to optimize one-time-use leaping mechanism for relocating energy-constrained sensor nodes. The leaping mechanism is expected to enhance coverage and connectivity of sensor networks initially randomly deployed with minimum energy consumed. Of particular interest is proper relocation of isolated nodes under uncertain environment conditions. Specifically, we consider how the aerodynamic disturbance can be minimized with an optimized launch angle of the leaping mechanism. To construct an automated simulation and design environment, the process integration and design optimization (PIDO) approach is employed. We not only obtain an optimum solution satisfying all imposed requirements, but also demonstrate an automated design process for controlled node mobility.**

I. INTRODUCTION

Wireless sensor networks to monitor physical or environmental conditions continue to gain increasing interest, due to their ad hoc nature, dispersability into hazardous areas, and disposability [1]-[5]. One of the most challenging and important issues in wireless sensor networks is how to maximize coverage of the network while simultaneously ensuring that nodes retain connectivity with one another. Because the initial locations of each sensor node are randomly deployed scattered by an airplane or other tools, some sort of node relocation strategy must accompany initial deployment of nodes to enhance network connectivity and coverage. Regarding possible solutions to this problem, there have been some researches imitating leaping behaviors of insects such as springtail, flea, or locust [6]-[8]. In spite of impressive leaping performances, their complicated structure and bulky size are inappropriate to be used for tiny, highly energy-constrained sensor nodes.

Under real world conditions, another equally important thing we should keep in mind to design the sensor node relocation mechanism is atmospheric conditions over the geographic area. Wireless sensor networks are frequently constructed to operate in hazardous environments. Therefore, in this paper, a simple yet efficient leaping mechanism for sensor node relocation is designed to operate in an autonomous, robust, and dependable manner even in adverse environmental conditions. Among many types of adverse conditions, an aerodynamic force which has significant effects on the sensor node leaping performance is considered. Specifically, the aerodynamic force is applied to the sensor node as a virtual force in the multi-body dynamics simulation for self-actuated mobility.

In this research, the Process Integration and Design Optimization (PIDO) [9] tool is used for automating the simulation and design environment. The major roles of PIDO, as its name depicts, are classified by two categories; integrating and automating several simulation processes into a unified simulation framework, and solving design problem with analytic design methodologies based on the framework. If the optimization technique is involved in the design stage and the commercial tools are used for simulations, the unified simulation framework is necessary because the optimization technique needs repetitive executions of simulations for converging to optimum solution. Besides, the PIDO offers many kinds of analytic design methodologies including the optimization technique, so the PIDO tool enables users to identify the better solutions more effectively. The PIDO was used for automating kinematic/dynamic simulation of the leaping mechanism in this research.

II. PRELIMINARY STUDY OF LEAPING PERFORMANCE

Schematic views of a mobile sensor node are shown in Fig. 1. It consists of node body part and projectile part, and the node body part includes electronic components for wireless communication. The projectile part has a fairly simple structure with eight one-time-use actuators (or pre-compressed springs) that use repulsive forces from the ground to leap over. The eight actuators are installed with the same interval to control the direction across an area as evenly as possible by selectively releasing the locking elements. In order to enhance network coverage and connectivity, the mobility parameters are required to be optimized for achieving accurate distance and direction control.

A preliminary study is conducted to examine how the possible combination of releasing actuators affects the leaping distance: changes in the leaping distance with respect to the number and combination of releasing actuators. Fig. 2 shows the changes in the leaping distance according to the number of releasing actuators. As shown in the figure, when the five actuators are released, the leaping distance is longer than other cases. Fig. 3 shows two kinds of combination with five actuators released, and their corresponding simulation results are shown in Fig. 4. According to the results, the leaping distance is maximized when five successive actuators

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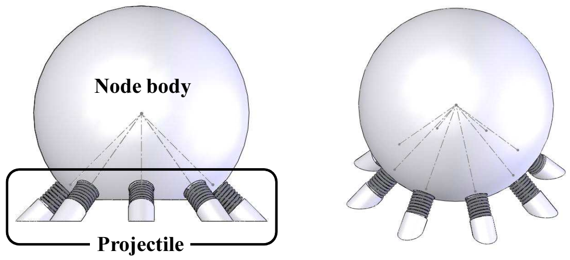


(a) front view (b) bird's eye view

Fig. 1. Schematic view of sensor node

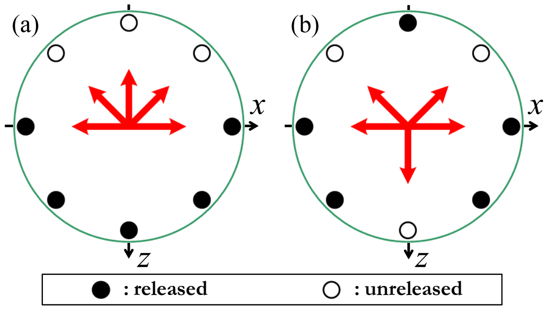


Fig. 3. Different releasing patterns of actuators ((a) successively released, (b) randomly released)

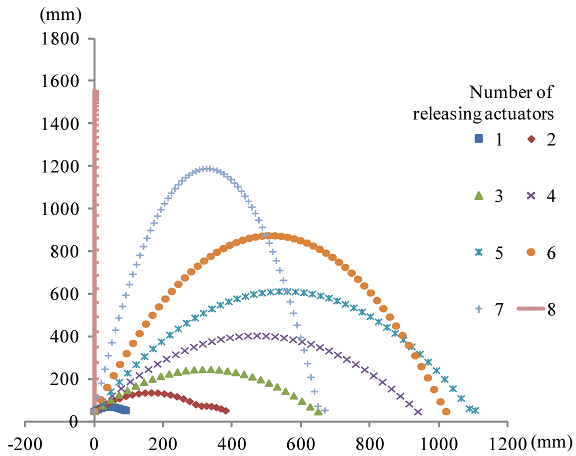


Fig. 2. Comparison of leaping simulations for the number of releasing actuators

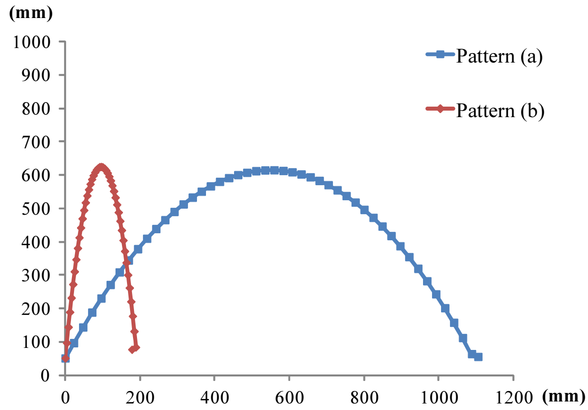


Fig. 4. Comparison of leaping simulations for actuating patterns

are released simultaneously. It does make sense because the theoretical resultant force of this case is larger than any other cases. Therefore, the combination of releasing actuators in Fig. 3-(a) is used in the rest of this work.

A preliminary study is conducted to examine how the possible combination of releasing actuators affects the leaping distance: changes in the leaping distance with respect to the number and combination of releasing actuators. Fig. 2 shows the changes in the leaping distance according to the number of releasing actuators. As shown in the figure, when the five actuators are released, the leaping distance is longer than other cases. Fig. 3 shows two kinds of combination with five actuators released, and their corresponding simulation results are shown in Fig. 4. According to the results, the leaping distance is maximized when five consecutive actuators are released. It does make sense because the theoretical resultant force of this case is larger than any other cases. Therefore, the combination of releasing actuators in Fig. 3-(a) is used in the rest of this work.

III. PARAMETRIC SIMULATION MODELING OF SENSOR NODE LEAPING MECHANISM

A. Parametric Representation of Actuating Force

Since the combination of actuators was determined to enhance the leaping distance in the previous section, what remains is how to decide the direction of actuating forces. The actuating forces can be parameterized by the locations of acting points and acting directions. Since the leaping mechanism has an axisymmetric structure as illustrated in Fig. 1, the location of acting point can be calculated only using a downward angle of x-axis for the center of mass of the node body, ϕ, and attaching angle of each actuator, θ. Because the actuators are attached to have the same interval, the attaching angle of each actuator can be calculated by dividing a plane into eight equal parts. In addition, the acting direction can be calculated by ϕ, θ, and another angular parameter, ψ, which is an upward angle of x-axis for the coordinate system centered at the acting point. The aforementioned angular parameters are graphically depicted in Fig. 5. As described above, the leaping mechanism proposed in this research is extremely simple both in structure and kinematics. Because of this simplicity, it is easy to build a simulation model and extend for relevant types of mechanisms. Furthermore, the proposed mechanism is an easy-to-handle design with just 3 kinds of design variables.

Now, the locations of acting points and directions can be calculated by three angular parameters, θ_s, ϕ, and ψ. Since the values of θ_s are fixed, by adjusting remaining two parameters, ϕ and ψ, the direction vector for the propulsion force can be generated. The location of acting point and direction can be calculated using (1) and (2).

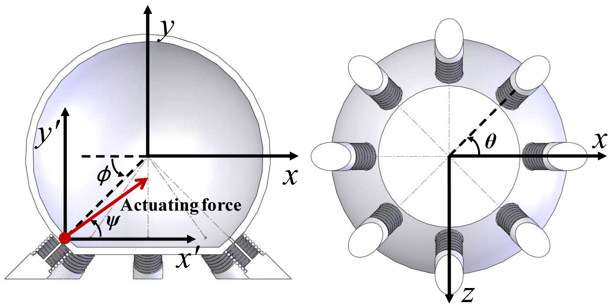


Fig. 5. Angular parameters of leaping mechanism

$$
\begin{aligned}
x_{ap} &= -L\cos\phi\cos\theta_i \\
y_{ap} &= H_{CM} + L\sin\phi \\
z_{ap} &= -L\cos\phi\sin\theta_i
\end{aligned} \quad (1)
$$

$$
\begin{aligned}
x_{ad} &= -L\cos\phi\cos\theta - L\cos\psi\cos\theta \\
y_{ad} &= {}_{CM} - L\sin\phi + L\sin\psi \\
z_{ad} &= -L\cos\phi\sin\theta - L\cos\psi\sin\theta
\end{aligned} \quad (2)
$$

In the above equations, x_{ap}, y_{ap}, and z_{ap} indicate the x, y, and z coordinates of acting points, respectively. In the same manner, x_{ad}, y_{ad}, and z_{ad} indicate the x, y, and z coordinates of acting directions, respectively. L and H_{CM} are the characteristic length for calculating the locations and the height of the center of mass of node body part. In this work, L is set to 49.5 mm and H_{CM} is 51.0374 mm.

B. Simulation Modeling of Aerodynamic Drag Force

This work aims to design a leaping mechanism which ensures reliable, accurate positioning of sensor node in the adverse operating condition. To accomplish this, we assume an area where the wind blows consistently at 10 m/s. The simulation model is constructed using a well-known multi-body dynamics analysis software Recurdyn [10]. In order to include the effect of aerodynamics, the drag force is applied to the sensor node as a virtual translational force over the area given by

$$F_D = \frac{1}{2}\rho\nu^2 C_d A \quad (3)$$

In (3), F_D, ρ, ν, C_d, and A indicate the drag force, the density of air, the speed of the wind relative to the object, the drag coefficient, and the reference area, respectively [11]. The density of air is 1.2 kg/m^3 and the drag coefficient C_d of the sensor node is assumed to be 0.47 [12]. The value of Cd for leaping mechanism is not easy to determine, because it is largely influenced by the phase and velocity of the surrounding fluid and shape of the object. However, the relative velocity between the sensor node and the air is not fast, and the density and viscosity of the air is very low. Therefore the value of Cd of the sensor node can be conclude as same as that of the sphere. The speed of the wind is set as 10 m/s. The drag force is automatically calculated for the relative velocity between the sensor node and the wind.

To identify the difference between the intended direction and simulated actual direction when the aerodynamic drag

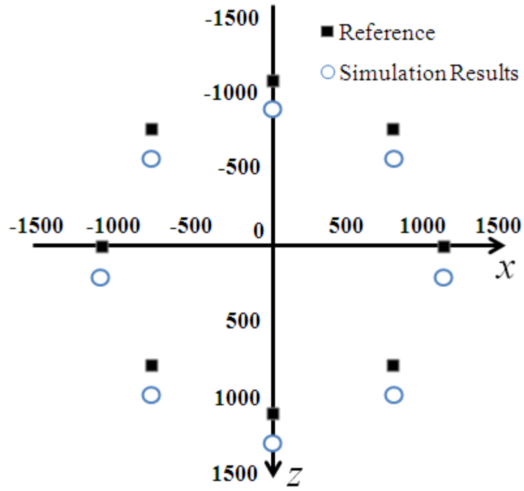


Fig. 6. Angular parameters of leaping mechanism

force is applied, simulations are performed for 8 directions. Here, the wind blows in the direction of z-axis and the results of the simulations are described in Fig. 6. As the figure indicates, the difference between the intended and actual directions is not negligible. Therefore additional enhancements of the directional control accuracy are needed.

IV. DESIGN OPTIMIZATION OF SENSOR NODE LEAPING MECHANISM

A. Process Integration for Leaping Performance Evaluation

Several analysis and simulation processes for evaluating the leaping performance are integrated and automated using a commercial PIDO software PIAnO [14] to perform the design more efficiently. The integration of the processes can be easily carried out using the PIDO technology, where various kinds of analytic design methodologies can be very helpful to find a design solution. Furthermore, once we make the integrated simulation environment, it can be easily extended for relevant types of leaping mechanisms by just changing some specifications of the mechanisms or simulation model. Since it can automatically save the simulation data used for design optimization, it is also very useful to manage and reuse the design data [20]-[22].

Fig. 7 shows the integrated simulation procedure in PIAnO to evaluate the leaping performance. Each box in Fig. 7 represents an analysis or simulation process, therefore eight kinds of analysis and simulation processes are used for evaluating leaping performances. In Fig. 7, “Preprocessor” component takes a roll of distributer for input variables to other analysis components. When a user inputs two angular parameters, ϕ and ψ, on this component, it gives the information to the “LocationData” component to calculate the locations of acting points and directions of actuating forces. The properties of sensor node such as the mass, the mass moments of inertia, the center of mass, and the configuration of actuators can be defined in the “Variable” component, and they are passed to the “RDP” component which defines

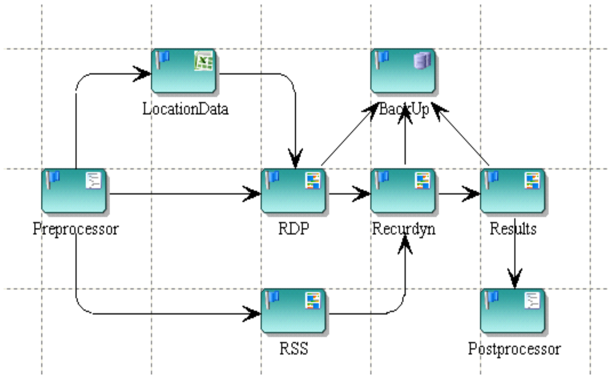


Fig. 7. Integrated analysis processes in PIDO environment

the topological information about the Recurdyn simulation model, and the "RSS" component which sets the condition of simulation. After the "RDP" and "RSS" components are successfully defined, the Recudyn simulation is conducted on the "Recurdyn" component. When the Recurdyn simulation is finished, the "Results" component analyzes the simulation output file and stores the information of flying trajectory of the sensor node. Finally the "Postprocessor" component extracts the landing location of the sensor node from the trajectory data. The topological input from the "RDP" component and simulation results files from the "Recurdyn" and the "Results" components are automatically saved via the "BackUp" component.

B. Formulation of Design Problem

As explained in Section II, the leaping distance and direction are the two most important performance characteristics in the design of our leaping mechanism. The leaping distance should be kept as long as possible to establish sufficient relocation capability, and the leaping direction should maintain a high level of accuracy with the intended direction. As Fig. 6 depicted, the accuracy of direction control is worst when the leaping direction and the wind blowing direction are perpendicular to each other. If the design satisfies the requirement imposed on the leaping direction even in this case, it will be a robust solution regardless of the wind blowing direction.

Since the interval between actuators and releasing combination of actuators are determined by extensive simulations in Section II, two remaining angular parameters which can represent the direction of actuating force, ϕ and ψ, are used as design variables to optimize leaping distance and direction accuracy. In this work, the leaping distance is considered as the objective function to be maximized. For the leaping direction control, a certain level of tolerable error, 5 degrees, is set as an upper limit of design constraint. A formulation of optimization problem is summarized in Eq. (4).

$$\begin{cases} Find & \phi \text{ and } \psi \\ to\ maximize & \text{Leaping Distance} \\ subject\ to & \text{Angular error} \leq \pm\, 5^\circ \end{cases} \tag{4}$$

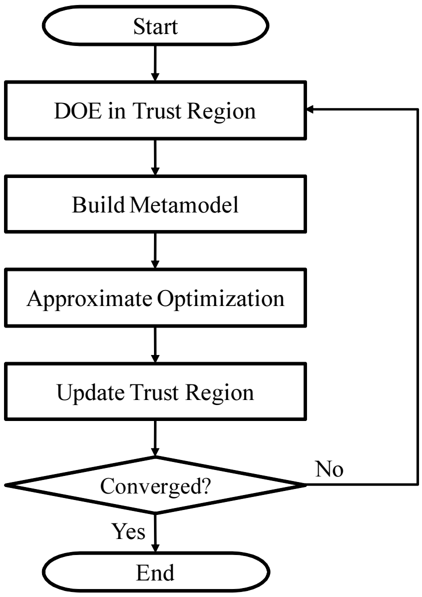


Fig. 8. Flow chart of PQRSM

TABLE I
OPTIMIZATION RESULTS

	initial	optimum	unit
ϕ	45.0000	40.9985	$deg.$
ψ	45.0000	26.2659	$deg.$
longitudinal dist.	1104.6286	896.8499	mm
lateral dist.	199.0191	78.1331	mm
overall dist.	1122.4139	900.2469	mm
angular error of direction	10.2133	4.9790	$deg.$

Among various optimization techniques, the Progressive Quadratic Response Surface Method (PQRSM) [15] is selected. PQRSM is one of the sequential approximate optimization techniques which involve the second order polynomial regression to approximate the performance responses and the trust region concept to manage the approximate region. Since it takes surrogates of the responses in the optimization procedure, it is suitable for noisy problems which have noisy behavior of responses. It is also well known for its outstanding efficiency and convergence ability. The overall algorithmic procedure of PQRSM is shown in Fig. 8. PQRSM has been applied to various kinds of design problems, and has proven its effectiveness in previous research [16]-[18].

C. Results of Design Optimization

Since the actuating angle to maximize the flying distance of the sensor node under gravity is 45 degrees, initial values of ϕ and ψ are set to 45 degrees. For the initial design, the longitudinal distance to leaping direction (leaping distance) and lateral distance (erroneous distance due to wind drag) are 1104.63 mm and 199.02 mm, respectively. Therefore the error of direction accuracy is larger than $\pm$ 10 degrees.

The performances of the initial and optimum design are

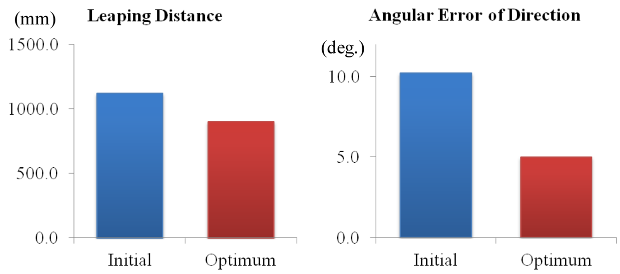
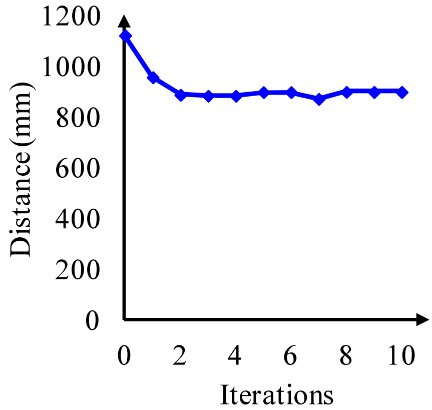


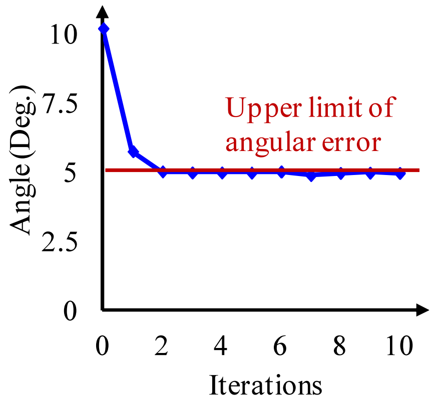
Fig. 9. Comparison of leaping performances between initial and optimum designs

compared in Fig. 9 and Table I. Although the distance is decreased by about 10%, the accuracy of directions satisfies the imposed requirement. Note that both design variables are decreased, and especially for ψ, which determines the direction of actuating forces, the optimum value is remarkably decreased from the initial one. It means that the horizontal component of the resultant actuating force is increased while the vertical component is decreased. The decrease in the vertical component of the resultant force brings the decrease in the leaping time. We can deduce that the optimum solution minimizes the effect of aerodynamic drag force by reducing the vertical component of the resultant force and the flying time. In addition, because the horizontal component of the resultant force is increased, the distance loss can be minimized. Convergence history plots of the distance and the direction error are shown in Fig. 10. It takes 10 iterations to get the optimum solution, and a total of 51 simulations are performed for design optimization.

Since the PIDO tool has various kinds of analytical design and performance evaluation methodologies, more information beyond the optimum solution is provided by the PIDO tool. Fig. 11 shows the leaping behavior of the optimum design case under the constant directional wind. Compared to Fig. 6, the accuracy of direction is enhanced. To further verify this, simulations are performed under uncertain wind direction conditions. Statistical behaviors of the leaping performances are observed by applying the Monte Carlo Simulation (MCS) [19]. The direction of wind is assumed to be an uncertain variable with uniform distribution from $0°$ to $360°$ in the x-z plane. The sample size of this statistical study is set to 500. Fig. 12 shows the histograms of the direction control errors caused by the uncertain wind direction, where initial errors appeared between $\pm\,10°$ are reduced to $\pm\,5°$ in the optimum design. Statistical comparison on the direction control accuracy of the initial and optimum design is given in Table II. As shown in Table II, the maximum error of the leaping direction is $10.3852°$ in the initial design, and it is reduced to $5.0110°$ in the optimum design. The reliability for the accuracy of direction, a probabilistic rate that the direction error is less than $5°$ is increased from 31.0% in the initial design to 95.4% in the optimum design. This result shows that the optimum solution is robust against uncertain wind blowing.



(a) leaping distance



(b) angular error

Fig. 10. Convergence history of design optimization

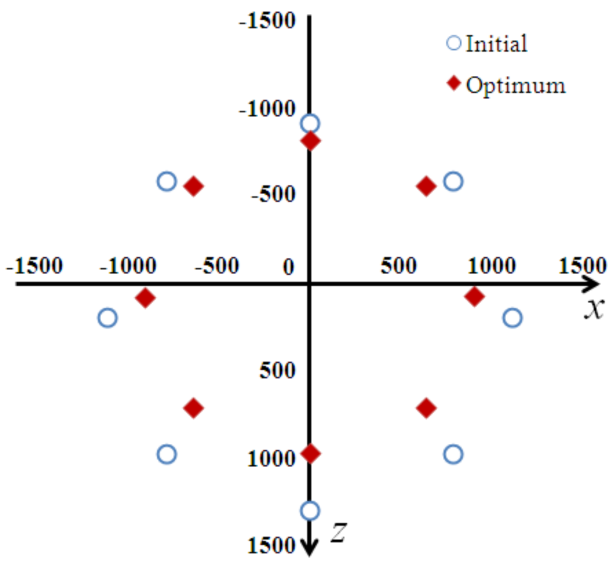
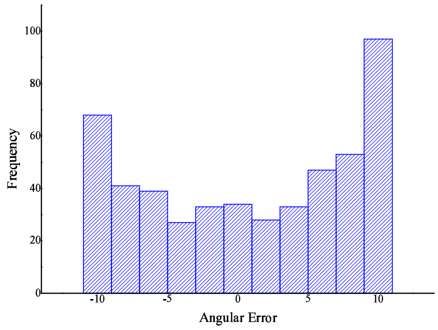


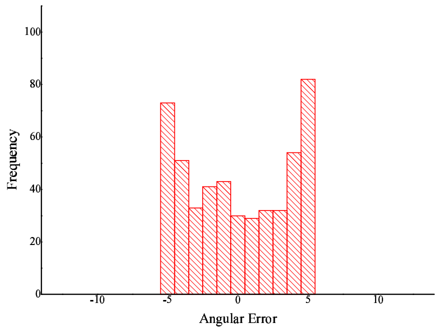
Fig. 11. Leaping simulation results for optimum design

V. CONCLUSIONS

The design optimization for the sensor node leaping mechanism was performed considering actual operating condi-



(a) initial design



(b) optimum design

Fig. 12. Histogram of angular error

tions. To enhance an applicability of the sensor node, severe operating condition for wind blowing was assumed and the aerodynamic drag force caused by the wind was applied to the leaping simulation. Several analysis and simulation processes for the evaluation of the leaping performance were integrated to efficiently perform the simulation and design, and the optimization technique was used to find the design solution of the leaping mechanism effectively. The optimum solution was verified by extensive simulations, where the accuracy constraint of the leaping direction was satisfied and the loss of the leaping distance was minimized. Most important, the major contributions of this work are not only the design optimization of the leaping mechanism, but also a systematic design procedure of such mechanisms by using the PIDO technology. The suggested design procedure is being applied for real sensor node development, and it is expected to be applied for other system designs in the same way.

TABLE II

STATISTICAL COMPARISON OF LEAPING ACCURACY

	initial	optimum
min. (deg)	0.0047	0.0050
max. (deg)	10.3852	5.0110
average	6.5630	3.2066
standard deviation	3.2210	1.5565
satisfying freq. of constraint	155	477
reliability (%)	31	95.4

REFERENCES

[1] K. Tadakuma, R. Tadakuma, and J. Berengueres, "Tetrahedral mobile robot with spherical omnidirectional wheel," *Journal of Robotics and Mechatronics*, 20(1):309-321, 2009.

[2] Y. D. Kim, Y. G. Kim, S. H. Lee, J. H. Kang, and J. An, "Portable fire evacuation guide robot system," *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, pp.2789-2794, 2009.

[3] K. Martinez, J. K. Hart, and R. Ong, "Environmental sensor networks," *IEEE Computer Journal*, 37(8):50-56, 2004.

[4] S. R. Madden, M. J. Franklin, J. M. Hellerstein, and W. Hong, "The design of an acquisitional query processor for sensor networks," *Proc. SIGMOD*, 2003.

[5] I. F. Akyildiz, W. Su, Y. Sankarasubamaniam, and E. Cayirci, "Wireless sensor networks: a survey," *Computer Networks*, 38(4):393-422, 2002.

[6] Y. Sugiyama, M. Yamanaka, and S. Hirai, "Circular/spherical robots for crawling and jumping," *Proc. IEEE Int. Conf. Robotics and Automation*, pp.3595-3600, 2005.

[7] M. Kovac, M. Schlegel, J.-C. Zufferey, and D. Floreano, "A miniature jumping robot with self-recovery capability," *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, pp.583-588, 2009.

[8] U. Scarfogliero, C. Stefanini, and P. Dario, "Design and development of the long-jumping 'grillo' mini robot," *Proc. IEEE Int. Conf. Robotics and Automation*, pp.467-472, 2007.

[9] F. Flager, B. Welle, P. Bansal, G. Soremekun, and J, Haymaker, "Multidisciplinary process integration and design optimization of a classroom building," *Journal of Information Technology in Construction*, 14:595-612, 2009.

[10] Recurdyn User's Manual, http://www.functionbay.co.jp

[11] A. P. French, *Newtonian mechanics* (1st ed.), New York: W. W. Norton and Company Inc., 1970.

[12] B. W. McCormick, *Aerodynamics, aeronautics, and flight mechanics*, New York: John Wiley and Sons, Inc., 1979.

[13] R. G. Watts and R. Ferrer, "The lateral force on a spinning sphere: Aerodynamics of a curveball," *American Journal of Physics*, 55(1):40-44, 1987.

[14] PIAnO User's Manual, http://www.iframax.com

[15] K. J. Hong, M. S. Kim, and D. H. Choi, "Efficient approximation method for constructing quadratic response surface model," *Journal of Mechanical Science and Technology*, 15(7):876-888, 2001.

[16] Y.-H. Kim, J.-H. Choi, S.-I. Jung, Y.-D. Chun, S. Kim, J. Lee, M.-S. Chu, K.-J. Hong, and D. H. Choi, "Optimal design of switched reluctance motor using two-dimensional finite element method," *Journal of Applied Physics*, 91(10):967-6969, 2002.

[17] J.-H. Choi, T. H. Kim, K.-B. Jang, and J. Lee, "Geometric and electrical optimization design of SR motor based on progressive quadratic response surface method," *IEEE Trans. Magnetics*, 39(5):3241-3243, 2003.

[18] G. Lee, J. H. Jeong, S. J. Yoon, and D. H. Choi, "Design optimization for optical patterns in a light-guide panel to improve illuminance and uniformity of the liquid-crystal display," *Optical Engineering*, 48(2):024001, 2009.

[19] N. Metropolis and S. Ulam, "The monte carlo method," *Journal of the American Statistical Association*, 44(247):335-341, 1949.

[20] I.-J. Hwang and G.-J. Park, "A multi-objective optimization using distribution characteristics of reference data for reverse engineering," *International Journal for Numerical Methods in Engineering*, 85(10):1323-1340, 2011.

[21] B.-L. Choi, D.-H. Choi, J. Min, K. Jeon, J. Park, S. Choi and J.-M. Ko, "Torsion beam axle system design with a multidisciplinary approach,"*International Journal of Automotive Technology*, 10(1):49-54, 2009.

[22] S. J. Yoon, S. H. Son, and D. H. Choi, "Head slider designs considering dynamic L/UL systems for 1-in disk drives," *IEEE Trans. Magnetics*, 44(1):151-156, 2008.