# COLLISION AVOIDANCE OF INDOOR FLYING DOUBLE TETRAHEDRON HEXA-ROTORCRAFT

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## Abstract

*The automatic flight of the multi-rotorcrafts is one of the hot topics of unmanned aerial vehicle systems. This paper is on collision avoidance control system of newly designed rotorcraft called double tetrahedron Hexa-Rotorcraft. The new rotorcraft has characteristic that the rotorcraft does not have to incline its attitude when the vehicle is moving in horizontal direction. This ability enables the craft to use the 2-dimentional laser range sensor to obtain the information of the surrounding environment. The control system uses laser range sensor to gather the information of unknown surrounding environment. The information amount feedback control is used for obtaining proper distance from the obstacle for safer flight. The results of numerical simulation, 2-dimensional vehicular test, and on-ground rotorcraft test are shown in the paper.*

## 1 Introduction

The automatic flight of the unmanned aerial vehicles (UAVs) is one of the hot topics in aeronautics. UAVs can be divided into fixed and rotary wing type. The different types of the wings give different type of characteristics for the vehicle such as payload, stabilization, surveillance, and etc... Amongst all, the multi-rotors have high payload and high stabilization. So-called quad-rotors are used to demonstrate the ability of the rotorcraft as future UAV system [1-3]. Compared to single-rotorcrafts, the multi-rotorcrafts have extra redundancy, extra payload, simple configuration, and higher stability for various missions. This characteristic makes multi-rotorcrafts a feasible system for UAVs.

The unmanned surveillance [4] of isolated indoor is currently one of the greatest interest in Japan due to the Fukushima nuclear plant accident. Currently there are no systems that can fly in indoor environment without having any information about the surrounding environment.

To achieve the unmanned surveillance for indoor, feasible collision avoidance system is needed for safer flight. For the fixed commercial planes, the TCAS II [5] is loaded for collision avoidance. Of course the system cannot be adopted for meter size UAVs. The collision avoidance strategy is studied amongst

Fig. 1 Photo of dot-HR

various field of automatic control. They start out from ships [6] to ground vehicles [7-9], and to the air vehicles [10-12]. These studies treat the information as certain, where all of the information is given for trajectory designing. The idea of information amount [13-16] is brought in to overcome the uncertainty of the environment which will be the problem in isolated environment.

In Yokohama National University, the hexa-rotorcraft with non-plane configuration is currently under development for automatic indoor surveillance of isolated environment. The rotor-craft has 6 rotors each at the edge of tetrahedrons placed in opposite of each other as shown in Figure 1. This rotorcraft is named double tetrahedron Hexa-Rotorcraft (dot-HR) from its unique configuration. The dot-HR has advantage that the vehicle does not need to incline when it is moving in horizontal direction where all of other rotorcrafts have to tilt its attitude toward the heading direction. This will enable the rotorcraft to easier system for visionary sensing, easier environment information monitoring by the laser range sensors and easier stabilization control for the vehicle can move around in its stabilized condition. These advantages are very large when the vehicle is moving in isolated area, where they have to find their way through the environment.

In this paper, the collision avoidance control law for dot-HR is introduced which will be loaded on the system for indoor surveillance in unfamiliar environment. The system of the dot-HR, avoidance control law using the information amount, simulation results of the collision avoidance, and 2-dimensional experiment results are presented in this paper.

## 2 Double Tetrahedron Hexa-rotorcraft

### 2.1 Rotorcraft Model

The dot-HR has 6 rotors placed in edges of the tetrahedrons placed opposite to each other. With tilt in the rotor axis, the vehicle is able to move around without tilting its attitude.

The state equation for the attitude can be written as follows.

$$\frac{d}{dt}\begin{pmatrix}\phi\\ \theta\\ \psi\\ \dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{pmatrix} = \begin{pmatrix}0&0&1&0&0\\ 0&0&0&1&0\\ 0&0&0&0&1\\ 0&0&0&0&0\\ 0&0&0&0&0\\ 0&0&0&0&0\end{pmatrix}\begin{pmatrix}\phi\\ \theta\\ \psi\\ \dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{pmatrix}$$
$$+\begin{pmatrix}0&0&0&0&0&0\\ 0&0&0&0&0&0\\ 0&0&0&0&0&0\\ 0&-C_{\ddot{\phi}}&-C_{\ddot{\phi}}&0&C_{\ddot{\phi}}&C_{\ddot{\phi}}\\ 2C_{\ddot{\theta}}&C_{\ddot{\theta}}&-C_{\ddot{\theta}}&-2C_{\ddot{\theta}}&-C_{\ddot{\theta}}&C_{\ddot{\theta}}\\ C_{\ddot{\psi}}&-C_{\ddot{\psi}}&C_{\ddot{\psi}}&-C_{\ddot{\psi}}&C_{\ddot{\psi}}&-C_{\ddot{\psi}}\end{pmatrix}\begin{pmatrix}T_1\\ T_2\\ T_3\\ T_4\\ T_5\\ T_6\end{pmatrix} \tag{1}$$

The $\phi$, $\theta$, and $\psi$ corresponds to roll, pitch, and yaw angles. $T$ is the thrust of each rotor. $C$ in the equation is calculated as follows.

$$C_{\ddot{\phi}} = \frac{C_{M_\phi}}{I_x} \tag{2}$$

$$C_{\ddot{\theta}} = \frac{C_{M_\theta}}{I_y} \tag{3}$$

$$C_{\ddot{\psi}} = \frac{C_{M_\psi}}{I_z} \tag{4}$$

The $l$ is the length of the rotorcrafts arm, $\alpha$ is the azimuth angle of the rotors, and $I$ is moment of inertia for each axis. Here, the $C_M$ are given as follows,

$$C_{M_\phi} = \frac{l}{6}\left(2\sin\alpha + \sqrt{2}\cos\alpha\right) \tag{5}$$

$$C_{M_\theta} = \frac{l}{18}\left(2\sqrt{3}\sin\alpha + \sqrt{6}\cos\alpha\right) \tag{6}$$

$C_{M\dot{\psi}}$ is the constant given by the relation of the counter torques by the rotors. From the characteristic that the dot-HR does not need to tilt its attitude, the system can be simply linearized and controlled with LQR to stabilize the attitude when flying.

The control input for motion is given as follows.

$$F = \begin{pmatrix} \cos\alpha & -\frac{1}{2}\cos\alpha & -\frac{1}{2}\cos\alpha & \cos\alpha & -\frac{1}{2}\cos\alpha & -\frac{1}{2}\cos\alpha \\ 0 & \frac{\sqrt{3}}{2}\cos\alpha & -\frac{\sqrt{3}}{2}\cos\alpha & 0 & \frac{\sqrt{3}}{2}\cos\alpha & -\frac{\sqrt{3}}{2}\cos\alpha \\ \sin\alpha & \sin\alpha & \sin\alpha & \sin\alpha & \sin\alpha & \sin\alpha \\ 0 & -C_{M_\phi} & -C_{M_\phi} & 0 & C_{M_\phi} & C_{M_\phi} \\ 2C_{M_\theta} & C_{M_\theta} & -C_{M_\theta} & -2C_{M_\theta} & -C_{M_\theta} & C_{M_\theta} \\ C_{M_\psi} & -C_{M_\psi} & C_{M_\psi} & -C_{M_\psi} & C_{M_\psi} & -C_{M_\psi} \end{pmatrix} u \tag{7}$$

$$F^T = (F_x \quad F_y \quad F_z \quad M_\phi \quad M_\theta \quad M_\psi) \tag{8}$$

$$u^T = (T_1 \quad T_2 \quad T_3 \quad T_4 \quad T_5 \quad T_6) \tag{9}$$

As for example when the rotorcraft are to move in horizontal direction, the thrust of the rotors 1 and 4 needs to be increased and others to be decreased. By their configurations, the motion could be done without tilting the attitude.

## 2.2 Sensors

The sensors on the rotorcraft can be divided into two categories. One is the inertial measurement unit(IMU), and the other is laser ranging sensor. The IMU measures the state of the rotorcraft and the laser range sensor measures the information of the surrounding environment.

The laser range sensor (URG-04LN; Hokuyo ; Figure 2) is loaded on dot-HR for environment sensing. The laser range sensor measures the range between the sensor and the wall in the environment. The sensor works approximately in 1Hz with 2.7 deg resolution and 1% of error in measurement. The sensor is ideal for indoor surveillance but can only measure in single plane. This makes the devise hard to be loaded on usual rotorcraft for they have to tilt when they move around, and in the other hand, makes it ideal to be loaded on dot-HR for sensing the obstacles and for automatic mapping.

# 3 Collision Avoidance Control

## 3.1 Information Amount Feedback Control

For autonomous surveillance in isolated indoors, feasible control law using the information from laser range sensor is needed.

The collision avoidance control based on the idea of information amount feedback is brought in. The information amount feedback quantizes the amount of information from the environment as physical value for the feedback control. The controller tries to obtain higher information amount then required information. The information amount is calculated from the total area of information obtained. Figure 3 shows the image of information amount.

$S_E$ is the focused area which evader is to search any obstacle/intruder. This area can be changed according to the designer's concept or environmental conditions. For example, when the vehicle is moving slowly, the area could be wide and short, when the vehicle is moving fast, the area could be narrow and long, according to the requirement. $S_C$ is the cleared area where the vehicle can obtain information. $S_B$ is the blocked area where the vehicle is unable to obtain information.

The parameter for information amount is defined as,


Fig. 2 Laser range sensor

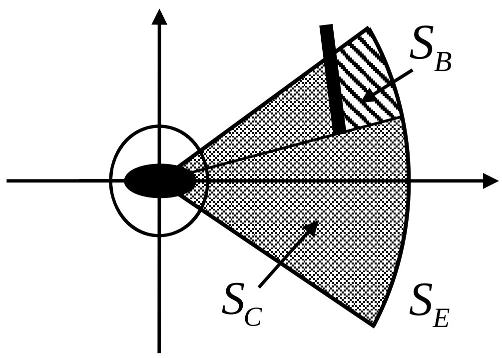


Fig. 3 Information amounts

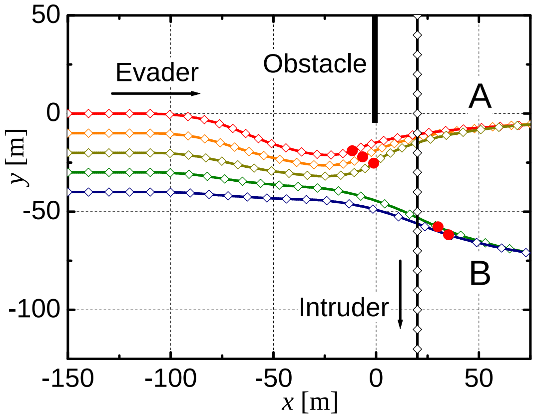


Fig.4 Numerical simulation: information amount feedback

$$I_L = \frac{S_C}{S_E}, \quad (10)$$

where, $I_R$ is called Information Localization which defines the percentage of the cleared area. This amount will define the availability of the information in focused area. The control law will try to obtain this value higher than certain desired value in order to avoid sudden collision.

When the vehicle is not in danger and the information amount is lower than the designated value, the information gathering control starts to obtain more information for the safer cruise. The input for steering control given as,

$$\delta = \frac{k}{(I_L - I_R)} \frac{(S_R - S_L)}{S_E}, \quad (11)$$

where, $I_R$ is required information amount, $S_R$ and $S_L$ is the cleared area in left and right of the focused area which gives the sign for the control. The vehicle will try to obtain enough information in order to avoid sudden dangers.

Applying this information amount feedback, the vehicle is able to obtain higher information about the surrounding environment which makes the vehicle safer to fly around with conventional control laws for navigation and collision avoidance.

## 4 Numerical Simulation

As an example for using information amount feedback control, some examples from numerical simulation are shown in this section.

The simulation is designed as environment for the conventional helicopters to fly in urban area with tall buildings shadowing the information [15]. Figure 4 shows the vehicle approaching from left side passing through environment with obstacle hiding the incoming intruder. 5 different cases are shown with different initial conditions. As the vehicle approaches the shadowed area, they make a right turn to obtain more information behind the obstacle. The evader makes smooth turn without having rapid turn to avoid the intruder. Based on this idea of the controller design, actual experiment using vehicle and rotorcraft is explained from next section.

## 5 Collision Avoidance Experiment

### 5.1 2-dimensional Vehicular Experiment

Prior to the rotorcraft experiment, 4-wheeled truck model as shown in Figure 5 is used to test the collision avoidance control law with information amount feedback. The 4-wheeled truck is loaded with the laser range sensor, and measures distance between the vehicle and the obstacle / intruder. This sensor demonstrates the environment of the actual information that can be obtained from eye sight or radar. The sensor scans the range of surrounding

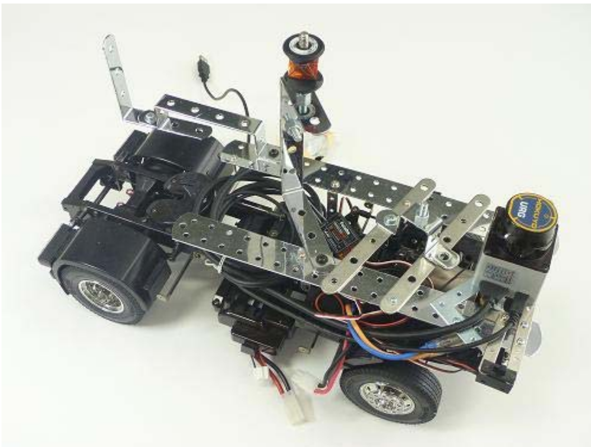

Fig.5 Vehicular experiment model

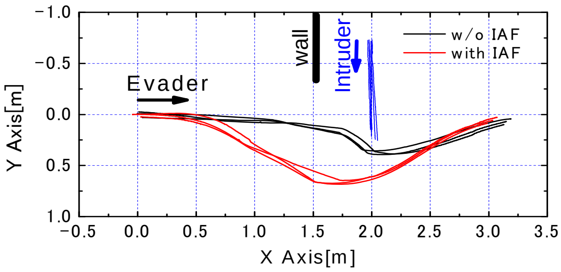


Fig. 6 Results of vehicular experiment

environment every 2.7 degrees. The environment data is transmitted to personal computer and goes through data processing, control law, and D/A converter. The output is send to the vehicle through the transmitter and the vehicle is controlled according to the control law.

The experiment is held with the control law explained in previous section. The intruder is model car that runs straight. The evader comes in with the designated course. The obstacle which lowers the information amount is set in right side of the designated course. The intruder starts behind this obstacle, so in case the evader has no collision avoidance system, the intruder will appear suddenly behind the obstacle and approaches the evader.

Figure 6 shows the trajectory of evader with and without information amount feedback. As the intruder approaches the course, evader must avoid the intruder. In the cases without information amount feedback, the evader finds the intruder very close to the wall because the laser range sensor is blocked by the obstacle close to the evader. After finding the intruder, evader takes a rapid turn to the right, and avoids the intruder. This is not a feasible control for real use, where system have use maximum input to avoid the accident.

In the other hand, the cases with the information amount feedback, the vehicle starts to obtain information after the obstacle is found in the designated range of the laser range sensor. After enough information is obtained, the vehicle keeps safety margin in between the intruder, and makes smooth curve after the risk of collision is gone. This motion is similar motion with that of humans when they are approaching the blind corner, where they cannot obtain enough information for safety.

## 5.2 2-dimensional Rotorcraft Experiment

The numerical simulation and vehicular test shows the feasibility of information amount feedback. The information amount feedback is loaded on the rotorcraft and tested to see feasibility of the system. The free flight testing requires several safety cautions to actually go through the test. In this paper the main thrust for the hovering will be reduced and the rotorcraft is placed on the jig which is able to

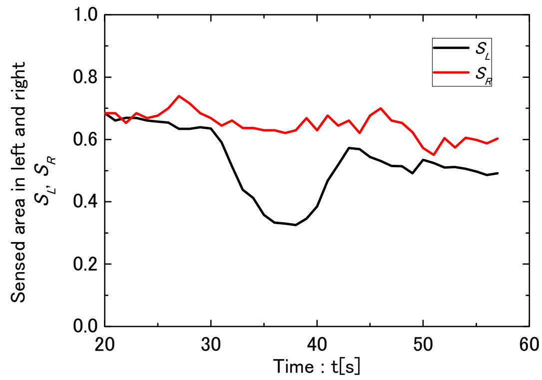


Fig.7 Time history of information amounts : straight

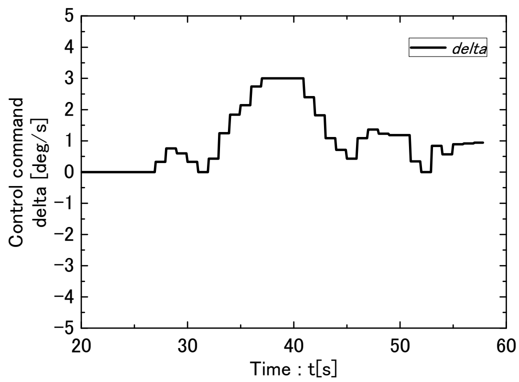


Fig.8 Time history of control command: straight

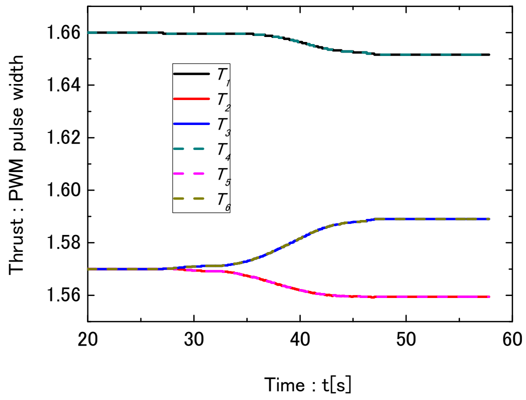


Fig.9 Time history of thrust input : straight

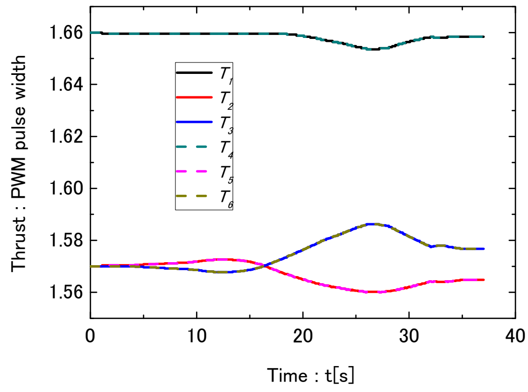


Fig.12 Time history of thrust input : curve

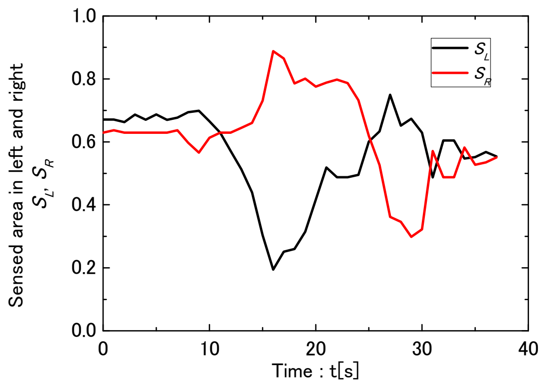


Fig.10 Time history of information amounts : curve

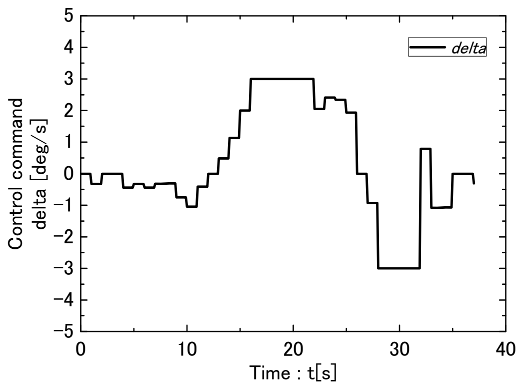


Fig.11 Time history of control command: curve

move in 2-dimensional plane. As first test, the jig moves straight forward in the isle with the blocking area in the left hand of the isle.

Figure 7 shows the time history of area obtained in right and left. As the $S_L$ decreases the system senses the obstacle. The control command for the information amount feedback is given as directional angle to obtain more information as shown in Figure 8. Figure 9 shows the time history of the thrust input for the rotors. We can see that the thrust is properly distributed according to the control command.

Figure 10 to 12 shows similar results with the case with the jig moving in 2-dimensional plane according to the thrust given by the control. In first half, the sensor finds the obstacle in the left, which reduces the $S_L$. As control input is given, the rotorcraft heads to right side. The area in the left increases as the rotorcraft moves, the input is given accordingly to the obtained data. From these results, control system has shown the ability to be loaded on the rotorcraft for actual flight testing.

## 6 Conclusion

The collision avoidance control law using information amount feedback for newly designed rotorcraft is introduced in this paper. The control law uses the information amount obtained by the laser range sensor loaded on the rotorcraft. The designed rotorcraft has ability to fly around in horizontal direction without tilting its attitude. The numerical simulation, vehicular experiment, and on-ground rotorcraft testing was held and examined. The results show that the system is ready to be loaded on the actual flight model for autonomous flight testing.

## References


[1] G. Hoffmann et al.: "The Stanford Testbed of Autonomous Rotorcraft for Multi Agent Control (STARMAC)", Proc. of the 23rd Digital Avionics Systems Conference, 12.E.4, 2004.

[2] N. Guenard et al. Dynamic modeling and intuitive control strategy for an "X4-flyer". Proc. of the 5th International Conference on Control and Automation, Budapest, Hungary, Vol. 1, pp 141-146, 2005.

[3] Rahul Goel et al. Modeling, Simulation and Flight Testing of an Autonomous Quadrotor. Proc. of the 11th Centenary International Conference and Exhibition on Aerospace Engineering, pp 18-22, 2009.

[4] D. M. Sobers et al.: "Laser-Aided Inertial Navigation for Self-Contained Autonomous Indoor Flight", Proc. of AIAA GNC Conference, AIAA Paper 2010-8211, 2010.

[5] "Introduction to TCAS II", U.S. Department of Transportation, Federal Aviation Administration, 1990.

[6] M. D.Ciletti, A. W. Merz and S. Takushoku, "Collision Avoidance Maneuver for Ships, Navigation –Japan Institute of Navigation-", 54, pp.83-89, 1977.

[7] T. Fukuda, N. Kubota, "An Intelligent Robotic System Based on a Fuzzy Approach", Proc. of the IEEE, 87-9, pp.1448-1470, 1999.

[8] T. Hiraoka, M. Tanaka, H. Kumamoto, T. Izumi and K. Hatanaka, "Collision Risk Evaluation Index Based on Deceleration for Collision Avoidance (First Report) : Proposal of a new index to evaluate collision risk against forward obstacles", Review of Automotive Engineering, 30-4, pp.429-437, 2009.

[9] T. Hiraoka, M. Tanaka, S. Takeuchi, H. Kumamoto, T. Izumi and K. Hatanaka, "Collision Risk Evaluation Index Based on Deceleration for Collision Avoidance (Second Report) : Forward obstacle warning system based on deceleration for collision avoidance", Review of Automotive Engineering, 30-4, pp.429-447, 2009.

[10] E. Frazzoli, Z. H. Mao, J. H. Oh and E. Feron, "Resolution of Conflicts Involving Many Aircraft via Semidefinite Programming", Journal of Guidance, Control, and Dynamics, 24-1, pp.79-86, 2001.

[11] D. J. Gates, "Properties of a Real-Time Guidance method Preventing a Collision", Journal of Guidance Control and Dynamics, 32-3, pp.705-716, 2009.

[12] A. Miele, T. Wang, J. A. Mathwig and M. Ciarcia, "Collision Avoidance for an Aircraft in Abort Landing : Trajectory Optimization and Guidance", Journal of Optimization Theory and Applications, 146-2, pp.233-254, 2010.

[13] S. Ueno, K. Iwama, T. Higuchi, "Collision Avoidance Control Law of Helicopter using Information Amount Feedback", Proc. of SICE Annual Conference, pp. 2118-2121, 2010.

[14] S. Ueno and T. Higuchi, "Collision Avoidance Law using Information Amount Feedback", Numerical Simulations, Intech Publishing, 2011

[15] T.Higuchi, S.Ueno and K.Iwama, "Collision Avoidance Control Law of a Helicopter using Information Amount Feedback", SICE Trans. on Industrial Applications, Vol. 10, No. 22, pp.182-189, 2011.

[16] T. Higuchi, K. Kokubu, and S. Ueno, "Experiment of Collision Avoidance Control Law with Information Amount Feedback", SICE Journal of Control, Measurement, and System Integration, 2012, (Accepted)


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