RESOURCE SCHEDULING STRATEGIES FOR A NETWORK-BASED AUTONOMOUS MOBILE ROBOT

Hongryeol Kim, Joomin Kim, and Daewon Kim

Department of Information Control Engineering, Myongji University

Abstract: In this paper, efficient resource scheduling strategies for a network-based autonomous mobile robot with hybrid robot control architecture are proposed. The basis of the resource scheduling strategies is the DMS(Deadline Monotonic Scheduling), and soft deadline and hard deadline are newly defined wit the DMS. A coordinated scheduling strategy configures the soft deadlines considering proceeding constraints for the minimization of behavior-to-behavior delays. A modulation strategy of the hard deadlines-rates is also proposed in this paper for the optimal usage of computational resource. The modulation is performed based on the dynamical values of the behaviors running on an operating system in each node. To compensate the uncertainty of the dynamical values inferred by sensor information, the fuzzy controls are used for the modulation, and the genetic algorithm is also used to refine the rate modulation result considering optimal real-time feasibility. Through simulation tests, scheduling results with the proposed strategies are compared with results without the proposed strategies to verify the performance enhancement by the proposed strategies.

Keywords: behavior, scheduling, network, robot, deadline, modulation, fuzzy control, genetic algorithm

1. INTRODUCTION

Various studies have been performed on network-based systems, since they enable conjunction of various heterogeneous systems and also minimize the cost for the conjunction. Recently, these studies are extending to such complicated systems as autonomous mobile robots for several purposes. Since most modern autonomous robots have hybrid robot control architectures(R.Alami, et al, 1998)(R.C.Arkin, and T. Balch, 1997)(Hongryeol Kim, et al., 2004) for both of planning capability and behavioral activity, a study for the hybrid robot control architecture on network-based system is also being performed(KITECH, 2004).

Since the hybrid control architectures are based on parallel computing environment, computational resource scheduling is very important for the control architecture. But unfortunately, computational resource scheduling on each independent node integrated with communication scheduling has possibility to bring unacceptable delay for the robot controls with the network-based robots. Additionally for the commercialization of the robots, the capacity of the computational resources will be constrained for competitive cost. Consequently, the minimization of the delay on the network-based system and optimal allocation of the computational resource are required for the network-based autonomous mobile robot.

In this paper, efficient resource scheduling strategies for a network-based autonomous mobile robot with hybrid robot control architecture are proposed. The basis of the resource scheduling strategies is the DMS(Deadline Monotonic Scheduling), and soft deadline and hard deadline are newly defined wit the DMS. A coordinated scheduling strategy configures the soft deadlines considering proceeding constraints for the minimization of behavior-to-behavior delays. A modulation strategy of the hard deadlines-rates is also proposed in this paper for the optimal usage of computational resource. The modulation is performed based on the dynamical values of the behaviors running on an operating system in each node. To compensate the uncertainty of the dynamical values inferred by sensor information, the fuzzy controls are used for the modulation, and the genetic algorithm is also used to refine the rate modulation result considering optimal real-time feasibility. Through simulation tests, scheduling results with the proposed strategies are compared with results without the proposed strategies to verify the performance enhancement by the proposed strategies.

2. HYBRID ROBOT CONTROL ARCHITECTURE FOR A NETWORK-BASED ROBOT

A picture of a network-based autonomous mobile robot is shown in Fig. 1. The robot is an assembly composed of brain module, sensor module, manipulator module, and mobile module. The functional modules are interconnected through the CAN(Controller Area Network) (Robert Bosch GmbH, 1991).

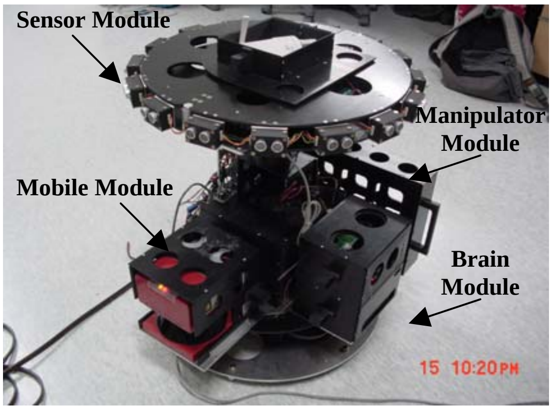

Fig 1. Network-based Autonomous Mobile Robot

A three-tiered hybrid robot control architecture for the above network-based robot, which is the basis of this study, is shown in Fig. 2(Hongryeol Kim, et al., 2004). As shown in the Fig. 2, the control architecture is composed of the planning layer, the executive layer and the behavior layer. The establishment of resource scheduling strategies is performed by the executive layer. On the behavior layer, the behaviors are processes running on the multi-tasking operating systems. Since the behaviors are distributed over the network system, interfaces among some behaviors are performed though the network communication.

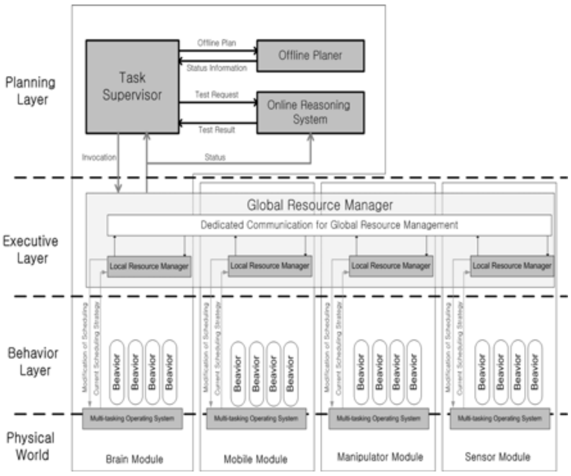

Fig. 2. Network-based Autonomous Mobile Robot

3. TIME PROPERTIES OF BEHAVIORS AND THEIR INTERFACES

Since function completion in time is required for the robot controls, real-time scheduler should be mounted with the multi-tasking operating systems in the Fig. 2. In this paper, the DMS is adopted for the scheduling strategy of the real-time scheduler. Since scheduling only with periodic tasks can guarantee the real-time feature of the DMS, all the behaviors are invoked periodically.

Real-time scheduling strategy should be also used for the arbitration of the CAN message. There are many studies devoted to the scheduling strategy with the arbitration mechanism of the CAN(K. M. Zuberi, K. G. Shin, 1997)(Marvo Di and Natale M., 2000)(Dukjin Pae, et al., 2002). In this study, the DMS is also adopted for the scheduling strategy of the CAN message arbitration.

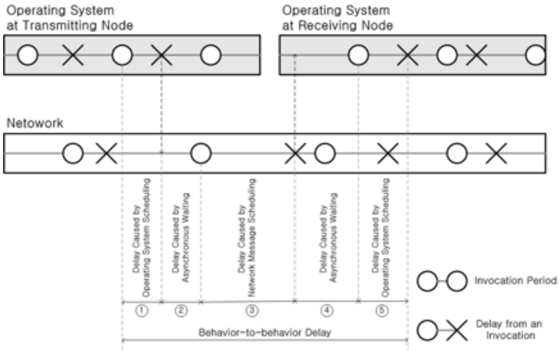

Fig. 3. Behavior-to-behavior Delay

Synthesis of the delay invoked while a message is generated from a behavior, transmitted to another behavior, and processed by the receiving behavior is shown in Fig. 3. As shown in the Fig. 3, behavior-to-behavior delay is composed of five elements. The first two elements are delays caused by the operating system scheduling at the transmitting node and the receiving node(① and ⑤ in the Fig. 3). The delays are composed of waiting time for behaviors with higher priorities, blocking time by behaviors with lower priorities, and computation time of itself. The worst case of the total delay(r_i) is represented by equation (1) and (2)(N.C Audesly, , et al., 1990). Where, C_i and C_j are computation times of behavior *i* and *j* individually, B_i is blocking time of task *i*, T_j is the release rate of the behavior *j*, $hp(i)$ is the set of behaviors with higher priorities than behavior *i*, and $lp(i)$ is the set of behaviors with lower priorities than behavior *i*.

$$r_i = C_i + B_i + \sum_{\forall j \in hp(i)} \left\lceil \frac{r_i}{T_j} \right\rceil C_j \tag{1}$$

$$B_i = \underset{\forall K \in lp(i)}{MAX}\ r_k \tag{2}$$

Since the behaviors on a node invoke periodically, the bandwidth utilization of each behavior is represented by equation (3). And for the meet of sufficient condition of real-time feasibility, the total bandwidth utilization of the periodic behaviors is constrained with equation (4)(T.W.Kuo and A.K.Mok, 1997). Where, *m* is the number of harmonic bases. Since only deadline is criteria for resource allocation with the DMS, the QoS(Quality of Service) of some behaviors, which are not critical but need high utilization of computational resource, cannot be guaranteed. To solve the QoS problem, rate modulation strategy will be proposed for the function of local resource manager in the Fig. 2.

$$U = \frac{C_i}{T_i} \tag{3}$$

$$\sum_{i=1}^{n} \frac{C_i}{T_i} \le m\left(2^{\frac{1}{m}} - 1\right) \tag{4}$$

The second element is delay caused by the CAN scheduling strategy with its arbitration mechanism(③ in the Fig. 3). Similar to the delay in operating systems as shown in the equation (1) and (2), the worst case of the total delay is composed of waiting time in message queue and transmission time. The waiting time in message queue includes waiting time by messages with higher priority, and blocking time by messages with lower priorities. The worst case of the total delay(r_m) is represented by equation (5) and (6) (Dukjin Pae, et al., 2002). Where, C_m is physical transmission time of message *m*, B is blocking time of message *m*, T_j is the release period of message *j*, $hp(m)$ is the set of messages with higher priorities than message m, and $lp(m)$ is the set of messages with lower priorities than message *m*.

$$r_m = B + \sum_{\forall j \in hp(m)} \left\lceil \frac{r_m + J_j}{T_j} \right\rceil C_m \qquad (5)$$

$$B = \underset{\forall K \in lp(m)}{MAX}\, c_k \qquad (6)$$

The third element is delays caused by asynchronous timing between operating system scheduling and the CAN message scheduling(② and ④ in the Fig. 3). In the Fig. 3, in case of message transmission from a behavior in transmitting node to network, real-time operating system in transmitting node is former step, and the network is latter step. Similarly, in case of message transmission from the network to a behavior in receiving node, the network is former step, and real-time operating system in receiving node is latter step. With the sequential phase stated above, the asynchronous waiting delay is invoked two times, when a message from the operating system in the transmitting node is waiting for transmission on the network, and also when the network message is waiting for handling by the operating system in the receiving node. To minimize the asynchronous waiting problem, a coordinated scheduling strategy will be proposed for the function of global resource manager in the Fig. 2.

4. RESOURCE SCHEDULING STRATEGIES FOR A NETWORK-BASED AUTONOMOUS MOBILE ROBOT

4.1 Coordinated scheduling strategy

In this paper, a coordinated scheduling strategy is proposed to reduce the asynchronous waiting delay, consequently to reduce whole behavior-to-behavior delay. For the scheduling strategy, new definitions of time properties of behaviors and messages are shown in the below:

① Rate(T_i)

Rate is defined as constraint condition of real-time of a behavior or a message. The rate has same meaning with the deadline of the DMS.

② Release Time($R_i(k)$)

Release time is defined as the instant when a behavior or a message is ready to start to be performed or be transmitted from idle status. The release time is defined with equation (7). Here, R_0 means initial release time, and k means release times of the behavior *i* or message *i*.

$$R_i(k) = (R_0 + k \times T_i) \qquad (7)$$

③ Computation Time(C_i) or Transmission Time(C_m)

C_i is computation time of behavior *i*. Similarly, C_m is transmission time of message *m*.

④ Deadline($D_i(k)$)

$D_i(k)$ is not such hard deadline as defined in the DMS, but soft deadline. The modulation range of the soft deadline is defined as equation (8).

$$0 < D_i(k) \le T_i \qquad (8)$$

⑤ Value($V_i(k)$)

$V_i(k)$ is relative run-time value of a behavior or a message at the instance *k*.

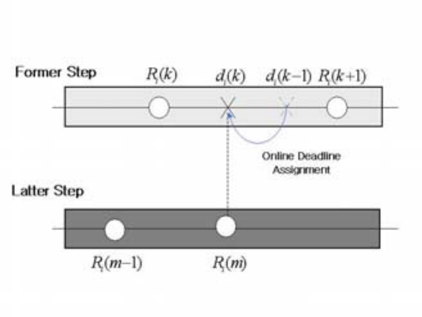

Fig. 4. Online Deadline Assignment

The coordinated scheduling strategy proposed in this paper is implemented with online assignment of the soft deadlines, and the deadline assignment($D_i(k)$) in the former step is determined as $R_i(m) - R_i(k)$ satisfying $R_i(m-1) < R_i(k) < R_i(m)$ in the latter step as shown in Fig. 4. The priority with the deadline assignment is determined according to the value of the former behavior or message. With the deadline assignment procedure, the admission control of the deadline assignment is performed for the bahaviors from *i=1*, to *i=n* with the equation (1). Similarly, the admission control of messages is performed for the messages from *i=1*, to *i=n* with the equation (3). The details of the procedure are described in the below:

Step1:
Align behaviors or messages in descending order of values from *i*=1 to *i*=*n*.

Step2:
Perform step 2 for *n* times from *i*=1 to *i*=*n* with following orders.

Step 2-1: At instance k of former step, find m of latter step satisfying $R_i(m-1) < R_i(k) < R_i(m)$.

Step 2-2: Perform admission control with new deadline candidate at instance k, $D_i(k) = R_i(m) - R_i(k)$.

Step 2-2: Assign the new deadline candidate to $D_i(k)$*, and perform Step2 with i+1, if the admission control is successful. Otherwise, perform Step3.*

Step3:

Perform step 3 for *n-(i-1)* times from *j=n* to *j=i-1* with following orders. When returned to Step3 again after *j=i-1*, perform Step2 from *i+1* with $D_i(k) = D_i(k-1)$.

Step 3-1: Perform admission control with new deadline candidate at instance k, $D_j(k) = T_j$.

Step 3-2: Assign the new deadline candidate to $D_i(k)$*, and perform Step2 with i+1, if the admission control is successful. Otherwise, perform Step3 with j-1.*

4.2 Rate modulation strategy

In this paper, a rate modulation strategy is proposed for the optimal QoS. The rate modulation is performed on the run-time values of behaviors and their messages. The values of the behaviors and their messages are decided by reactive planner on the planning layer in the Fig. 2. Since the reactive planer makes decisions with uncertain perceptions, the values are also uncertain. To compensate these uncertainties, the local resource manager has its own fuzzy controllers to fuzzify the values decided by the planner. The outputs of the fuzzy controllers are defuzzified into rate modulation results. The rate modulation results are refined within the allowable DMS constraints to get optimal results considering harmony of the rates. The construction of computational resource manager with abstract reactive planning closed loop is shown in Fig. 5.

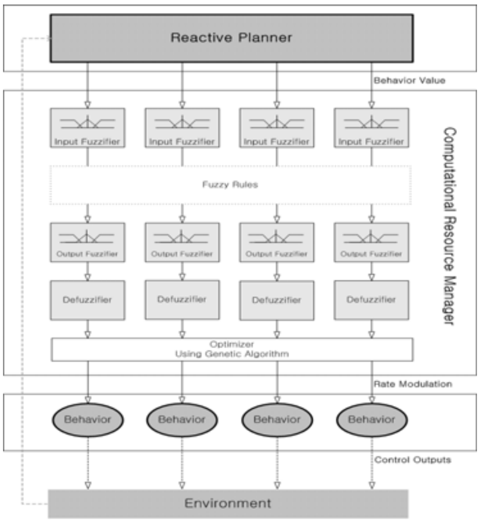

Fig. 5. Computational Resource manager

Value judgments have been studied for goal achievement in intelligent systems(A.M.Meystel and J.S.Albus, 2002). Values of behaviors are computed by value judgment functions residing in the reactive planners. The value judgment mechanism can be defined with equation (9). Where, $e(j,t)$ is the value of *jth* value vector at time *t*, $s(i,t)$ is the state of the *ith* state vector at time *t*, $w(i,j)$ is weight, that defines the contribution of $s(i)$ to $e(j)$, and *k* is a coefficient that defines the importance of derivation in the value judgment.

$$e(j,t+dt) = (k\frac{d}{dt}+1)\sum_i s(i,t)w(i,j) \qquad (9)$$

In the view of control theory, rates of the behaviors can affect the stabilities of the behavior controls. Since most of current behaviors are implemented into discrete systems, the sampling rate constraint for control stability of discrete system(K.J.Astrom and B.Wittenmark, 1997) is adopted in this paper. This constraint defined with equation (10) is used for the decision of allowable maximum and minimum rate. Where, T_i^r is system rising time of i_{th} task.

$$4 \le \frac{T_i^r}{T_i} \le 10 \qquad (10)$$

The rate modulation results from the fuzzy controls should be refined to meet to maintain its control stability and to keep real-time constraints defined with the equation (1) and (4). In this paper, the genetic algorithm is used for refining the rate modulation results within allowable range defined with the equation (1), (4), (10), and possibly with less harmonic bases using fitness function represented with equation (11). The chromosomes for the genetic algorithm and their genetic operations are shown in Fig. 6. In the Fig. 6, a chromosome is proposed to have rates of all behaviors from the least prioritized behavior in the left to the most prioritized behavior in the right, and there are 3 genetic operations for next generation. Anyway with any genetic operation, chromosomes that violate the real-time constraints and chromosomes that change priority order from the rate modulation results by the fuzzy controls are not generated through heuristic admission controls.

$$Fitness = \frac{1}{m} \qquad (11)$$

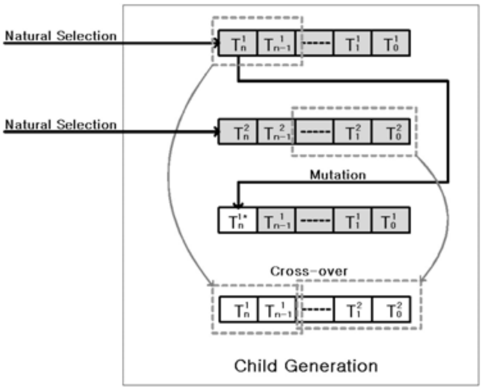

Fig. 6. Chromosomes and Genetic Operations

5. SIMULATION TESTS

In the following simulation tests, the autonomous mobile robot should avoid obstacles and reach a target, concurrently with transmitting gathered environmental information to its remotely located master by wireless communication. Time properties of behavior sets and message sets for the simulation tests are shown in Table 1. For the obstacle avoidance, the **B1** behavior in the brain module transmits control data to the **M1** behavior in the mobile module through the **CAN1** message. And the **B6** behavior in the brain module performs the function of the environmental information transmission.

In this paper, only the rate of the behavior **B1** and **B6** are modulated according to the proposed rate modulation strategy for the simplicity of the simulation tests.

$$e(t+dt)=(7\frac{d}{dt}+1)(1000-s(t)) \qquad (12)$$
$$(if\ e(t+dt)\le 0, e(t+dt)=0)$$

Table 1. Time Properties of Behavior Set and Message Set for Simulation Test

	Behavior	C_i [mS]	T_i [mS]	T_r [mS]
Brain Module	**B1**	20	400	2000
	B2	20	400	2000
	B3	20	600	6000
	B4	20	800	8000
	B5	50	1600	16000
	B6	100	3200	16000
Mobile Module	**Behavior**	C_i **[mS]**	T_i **[mS]**	T_r **[mS]**
	M1	20	500	5000
	M2	20	700	10000
	M3	50	700	10000
	M4	50	1000	10000
	M5	100	1000	10000
CAN Message	**Message**	**Size [Byte]**		T_i **[mS]**
	CAN1	8		600
	CAN2	8		600
	CAN3	8		600
	CAN4	8		600
	CAN5	8		600

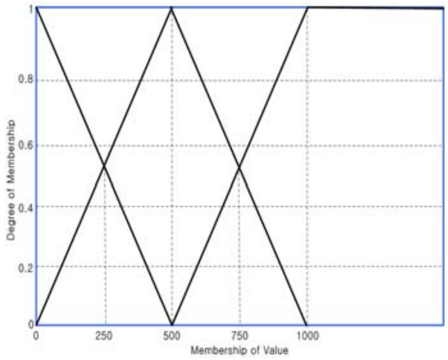

Fig. 7. Input Membership Functions

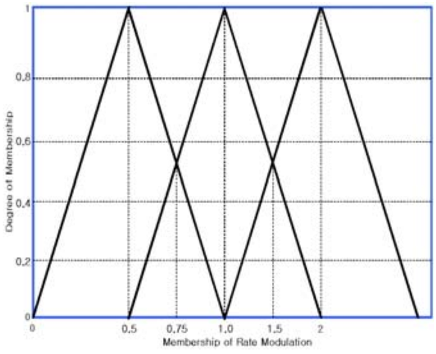

Fig. 8. Output Membership Functions

For the rate modulation control, the fuzzy control with one input and one output is implemented. In the fuzzy control, value calculated by equation (12) is considered as fuzzy input. In the equation (12), *s(t)* is a sensory input that represents the minimum distance in centimeter to surrounding obstacles. The sensory input is calculated in a multiple channel ultrasonic sensor module. Input membership functions and output membership functions for the fuzzy control are shown in Fig. 7 and Fig. 8. Simple inference rules for the fuzzy control are same as following:

(1) *If the value is 250, the rate of the obstacle avoidance is modulated by 2.0 times, and the rate of the information transmission is modulated by 0.5 times.*

(2) *If the value is 500, the rate of the obstacle avoidance is modulated by 1.0 time, and the rate of the information transmission is modulated by 1.0 time.*

(3) *If the value is 1000 ,the rate of the obstacle avoidance is modulated by 0.5 times, and the rate of the information transmission is modulated by 2.0 times.*

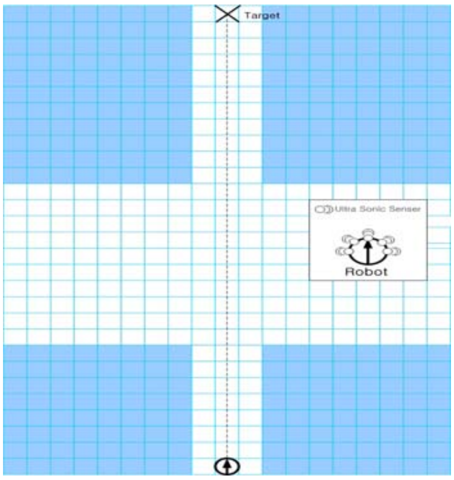

Fig. 9. Simulation Environments

Tests are performed on simulated environments shown in Fig. 9. As shown in the Fig. 9, the robot has 5 ultrasonic sensors and the size of a grid is 30 square centimetres. The size of the robot is also 30 square centimetres. Because the robot for the simulation tests is equipped with ultrasonic sensors, sensory inputs of the minimum distance to obstacles are modelled with Gaussian probability distribution in the test(Borenstein J. and Koren Y., 1991). For refining rate modulation through the genetic algorithm, the population size of the one-generation is 100, and total 100 generations are created for a chromosome with the best fitness value.

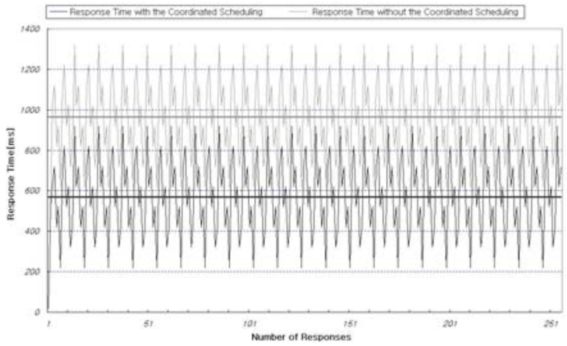

Fig. 10. Behavior-to-Behavior Response Time

In Fig. 10, the behavior-to-behavior response time of message transmission from the **B1** to the **M1** through the **CAN1** with the proposed coordinated scheduling strategy is compared to behavior-to-behavior response time of it without the proposed strategy. As shown in the Fig. 10, the average of the behavior-to-behavior response time with the proposed strategy is 568*mS*, while the average of the behavior-to-behavior response time of it without the proposed strategy is 965*mS*. The response time with the coordinated scheduling is reduced by about 40%.

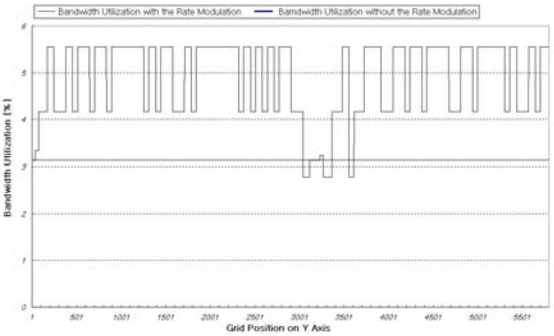

Fig. 11. Bandwidth Utilization of **B6**

In Fig. 11, the bandwidth utilization of the **B6** with the proposed rate modulation of the **B1** and the **B6** is compared to bandwidth utilization of it without the modulation strategy. The bandwidth utilization of the **B6** with the proposed rate modulation is higher than the constant bandwidth utilization of the **B6** without the proposed rate modulation in most time. The bandwidth utilization of the B6 with the proposed rate modulation is lower than the bandwidth utilization of the **B6** without the proposed rate modulation for a moment when the robot meet narrow path.

5. CONCLUSIONS

In this paper, efficient resource scheduling strategies for a network-based autonomous mobile robot with hybrid robot control architecture are proposed. The scheduling strategies are for the minimization of behavior-to-behavior delays when behaviors communicate with others over network, and for the optimal usage of computational resource on each network node of the robot. The basis of the resource scheduling strategies is the DMS. In this paper, soft deadline and hard deadline are newly defined wit the DMS, the soft deadlines of behaviors or messages are modulated through coordinated scheduling strategy for the minimization of the behavior-to-behavior delays. The coordinated scheduling strategy configures the soft deadlines considering proceeding constraints. A modulation strategy of the hard deadlines-rates is also proposed in this paper for the optimal usage of computational resource. The modulation is performed based on the dynamical values of the behaviors running on an operating system in each node. To compensate the uncertainty of the dynamical values inferred by sensor information, the fuzzy controls are used for the modulation, and the genetic algorithm is also used to refine the rate modulation result considering optimal real-time feasibility. Through simulation tests, scheduling results with the proposed strategies are compared with results without the proposed strategies to verify the performance enhancement by the proposed strategies. From the simulation test, it is verified that the behavior-to-behavior response time with the proposed coordinated strategy is reduced from the response time without the strategy. And it is also shown that the utilization bandwidth can be increased with the proposed rate modulation strategy

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