2014 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)
July 6-11, 2014, Beijing, China

Intention Recognition by Inverted Two-Wheeled Mobile Robot through Interactive Operation

Yasutake Takahashi, Takuya Inoue, and Takayuki Nakamura

***Abstract*— Recently, two-wheeled inverted pendulum mobile robots have been popular. They support human locomotion and/or small goods transportation based on inverted pendulum upright controllers. The conventional inverted pendulum mobile robot controls to follow the fixed desired posture angle and wheel velocity. It is desirable to change the control parameters according to the user intention in order to offer comfortable operability of the robot. This paper proposes a user intention recognition system for a inverted pendulum mobile robot and shows experimental results.**

I. INTRODUCTION

Recently, robots working in human symbiotic environment have been studied and developed. Two-wheeled inverted pendulum mobile robots have been developed as a realistic solution for the human symbiotic environment so far[1][2]. The inverted pendulum mobile robot has many advantages over statically stable wheeled robots and other biped robots. It requires less space to stand and stay upright than ordinary wheeled mobile robots and a smaller number of actuators than conventional biped robots. They support human locomotion and/or small goods transportation based on inverted pendulum upright controllers[3][4].

Fig. 1. Porter Robot based on Wheeled Inverted Pendulum System

Fig.1 shows a concept of a porter robot based on a wheeled inverted pendulum mobile system. The robot stands by itself if the user leaves it alone. The user operates the robot by pulling the handle, then, the robot assists the power of the pulling and follows the user. It is useful especially for elderly people or disease patients because it needs less power to transport a heavy equipment for the user.

The most conventional inverted pendulum mobile robot controls to follow the fixed desired posture angle and wheel velocity. It is necessary to change the control parameters according to the user intention in order to offer more comfortable operability of the robot. It is practical to use a button to switch the control parameters by hand as proposed in [4], however, it is more desirable to change them without the special button but with the user natural operation of the cart. Realtime user intention recognition is needed for the porter robot based on the wheeled inverted pendulum mobile system.

Estimating the user intention through physical interaction between a human user and a mobile robot is an interesting research topic. Takeda et al.[5], [6] show a dance partner robot that estimates dance step of a human user based on the force sensors that touch the human and sense the force added by the human. They use hidden Markov models to estimate the steps of the human using sequences of sensor outputs. They assume that the human changes his step in time to music. Dance music has tempo so that the robot easily adjust the timing of step estimation. Unfortunately, the assumption cannot be applied to our porter robot because a potential user changes his/her behavior to the robot whenever he/she wants. They also implicitly assume that the robot stays while the human starts his step because the robot is heavy enough to resist the pushing or pulling force by the human. The assumption makes the estimation simple because it does not have to take the robot control parameters into consideration. Unfortunately, the porter robot changes its control parameters depending on the situation of human operation. For example, if the user leave the porter robot alone, the robot just controls itself to stand in upright position to avoid falling down. If the user starts to pull the handle of the robot, it changes the desired posture angle and the gain corresponding to the desired wheel angle velocity to support the user.

This paper proposes a user intention recognition system for a porter robot based on wheeled inverted pendulum mobile system. It recognizes four behaviors of the user, leaving the robot standing, starting to pull the robot, continuing the pulling, and returning the robot in upright position, in real time. The recognition system remembers the sequence of the robot sensor outputs during the four behaviors of the human user. It estimates the human behavior every 50 [ms] base on gaussian models of the sequences of the robot sensor outputs corresponding to the four human behaviors. The robot changes the desired posture angle and the control gain corresponding to the desired wheel angle velocity according to the behavior of the user in order to assist the user. Experimental results show the validity of the proposed recognition system.

Yasutake Takahashi and Takuya Inoue are with the Department of Human and Artificial Intelligence Systems, Faculty of Engineering, University of Fukui, 3-9-1, Bunkyo, Fukui, Fukui, 910-8507, Japan (email: {tinoue, yasutake}@ir.his.u-fukui.ac.jp).
Takayuki Nakamura is with the Faculty of Systems Engineering, Wakayama University, Sakaetani 930, Wakayama 640-8510, Japan (email: ntakayuk@sys.wakayama-u.ac.jp).

II. Overview of Intention Recognition for Inverted Mobile Robot

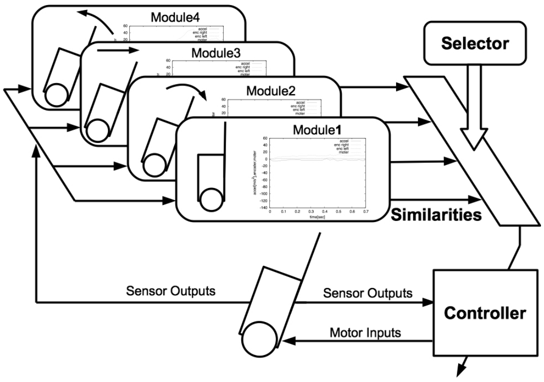


Fig. 2. Schematic View of User Intention Recognition System

Fig. 2 shows a basic architecture of the proposed user intention recognition system. The wheeled inverted pendulum mobile robot has a two-directional acceleration sensor and one rate gyroscope for detection of body posture. A Kalman filter is applied for accurate estimation of the body posture. It also has one encoder for each wheel to detect the wheel angle velocity. A simple posture controller for the wheeled inverted pendulum mobile robot is embedded to the realize the desired posture and the desired wheel velocity of the vehicle. The details is described in IV.

A modular system is adopted for the user intention recognition system. Each module has a motion template that corresponds to one intention/behavior of the user. User intentions/behaviors are leaving the robot standing, starting to pull the robot, continuing the pulling, and returning the robot in upright position. One motion template maintains a sequence of sensory outputs and motor inputs and their variances that corresponds to the assigned intention/behavior. The module receives a sequence of sensory outputs and motor inputs, compares it to its motion template, and calculates the similarity in real time as described in III.

The selector receives the similarities from the modules, selects one intention/behavior of the user, and sends the desired posture and the control gain corresponding to the desired wheel velocity to the posture controller of the wheeled inverted pendulum mobile robot. The selector has to change the desired posture and desired wheel velocity according to the user intention/behavior appropriately. When the user puts the robot in upright position, the desired posture should be at the right balance point otherwise the robot starts to run. The desired wheel velocity and the control gain corresponding to the velocity are set to zero and high value, respectively, in order to keep the robot to stay. When the user starts to pull the robot, the desired position changes to incline the robot body to the user for comfortable operation of the robot as shown in Fig.1. The control gain corresponding to the wheel velocity is set to zero so that that robot follows the user.

III. Intention Recognition Module

An intention recognition module has a motion template that corresponds to one intention of the user. The motion template maintains a sequence of sensory outputs and motor inputs $\boldsymbol{\mu}_t$ and their variances $\boldsymbol{\sigma}_t$ that corresponds to the assigned intention. The center of the template $\boldsymbol{\mu}_t$ and the variance $\boldsymbol{\sigma}_t$ include the estimated body posture angle based on the outputs of two-directional accelerometer x_a, one rate gyroscope x_g, wheel encoder output x_e, and input to the wheel motor x_u at time t. $\boldsymbol{x}_t$ indicates the sensory outputs and motor inputs at time t. The similarity g of the template $(\boldsymbol{\mu}_t, \boldsymbol{\sigma}_t)$ and the sequence of sensory outputs and motor inputs of the robot $\boldsymbol{x}_t = (x_a, x_g, x_e, x_u)$ is calculated as below:

$$g = \sum_{t=1}^{T} \exp(-(\boldsymbol{x}_t - \boldsymbol{\mu}_t)^{\mathrm{T}} \Sigma_t (\boldsymbol{x}_t - \boldsymbol{\mu}_t)) \tag{1}$$

where the T and Σ_t is the length of the template sequence and the variance matrix that has the element of the variance vector $\boldsymbol{\sigma}_t = (\sigma_a, \sigma_g, \sigma_e, \sigma_u)$ in diagonal. T indicates transposition of the vector.

In order to prepare the template $(\boldsymbol{\mu}_t, \boldsymbol{\sigma}_t)$, some data are needed to collect. First, we prepare one sequence data including the estimated body posture angle, the encoder output, and the motor input, $\boldsymbol{d}_t = (d_a, d_e, d_u)$, for each behavior of the user. Then, a simple weighted mean square error is used to collecting the data for the each behavior.

$$e = w_a \sum_{t=1}^{T} (d_a - x_a)^2 + w_e \sum_{t=1}^{T} (d_e - x_e)^2 + w_u \sum_{t=1}^{T} (d_u - x_u)^2 \tag{2}$$

where w_a, w_e, and w_u are normalization coefficients. If the weighted mean square error e is the smallest than the other and less than predefined threshold e_{thre}, the sequence sensor outputs and motor inputs is recorded as the data for the behavior. Then the template $(\boldsymbol{\mu}_t, \boldsymbol{\sigma}_t)$ is calculated as blow.

$$\boldsymbol{\mu}_t = \frac{1}{N} \sum_{n=1}^{N} \boldsymbol{x}_t^n \tag{3}$$

$$\boldsymbol{\sigma}_t = \frac{1}{N} \sum_{n=1}^{N} (\boldsymbol{x}_t^n - \boldsymbol{\mu}_t)^{\mathrm{T}} (\boldsymbol{x}_t^n - \boldsymbol{\mu}_t) \tag{4}$$

where n, N, and $\boldsymbol{x}_t^n$ indicate index and number of the data, and the sensor outputs and motor inputs at time t of the nth data.

The recognition system based on the simple weighted mean square error has an advantage of simple and light computational cost, however, there are many parameters, e.g., the normalization coefficients w_a, w_e, w_u and the threshold e_{thre} that have to be tuned well through trial and error. Unfortunately, it does not show robust recognition in our experiments. However, it can be used for data collection for the templates of user intention. We choose the data for the calculation of the means and variances of the template after we check the data seems to be correct or not. Furthermore, the calculation of the similarity, Eq.(1), makes the recognition system to be tolerant to the variation of the sensory outputs and motor inputs because of the term of variance.

IV. Posture Controller for Wheeled Inverted Pendulum Mobile Robot

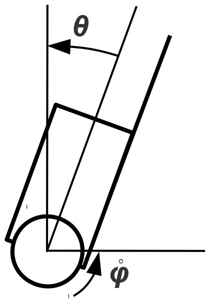


Fig. 3. Model of the Wheeled Inverted Pendulum Mobile Robot

Fig. 3 shows the model of our wheeled inverted pendulum mobile robot. The posture angle θ is estimated by a Kalman filter using two-directional accelerometer and one rate gyroscope. The Kalman filter is a typical one so that the detailed description of the Kalman filter is omitted in this paper. The wheel angular velocity is measured with an encoder attached to the motor.

The posture controller follows conventional torque control theory. Torque for the wheels u is calculated as follows:

$$u = -k_1(\theta - \theta_d) - k_2\dot{\theta} - k_3\dot{\varphi} - k_4\int_t(\dot{\varphi} - \dot{\varphi}_d), \quad (5)$$

where θ, θ_d, $\dot{\theta}$, $\dot{\varphi}$, $\dot{\varphi}_d$, and t are body angle, desired body angle, angular velocity of the body, wheel angular velocity, desired wheel angular velocity, and time, respectively. k_1, k_2, k_3, k_4 are gains for the body angle, body angular velocity, wheel angular velocity, and accumulated error of wheel angular velocity, respectively.

V. Experiments

Fig. 4 shows the porter robot based on a wheeled inverted pendulum mobile robot that we designed and built. We set up the experiment as follows:

1) record one sequence of sensor outputs and motor inputs for each user intention
2) recognize the user intention based on the simple weighted mean square error using the recoded sequences in 1) and collect the data for the template corresponding to the user intention
3) calculate the means and variances of each template
4) recognize the user intention based on the similarities of the templates.

Fig. 5 shows typical sequence of sensor outputs and motor inputs corresponding to the user intentions, e.g., leaving the robot standing, starting to pull the robot, continuing the pulling, and returning the robot in upright position. Fig.6 shows an example of the result of the intention recognition based on the simple weighted mean square error. While the porter robot stays in upright position, the error of the "stay in upright position" behavior is smaller than the others. When the user starts to pull the porter robot at time 5.2 [s], the error of the "stay in upright position" behavior becomes higher and the error of the "start pulling" behavior becomes small instead, as shown at ①. While the user keeps pulling the porter robot, the error of "keep pulling" behavior becomes small as shown at ②. When the user pull back the porter robot to make it stay in upright position, the error of "returning in upright position" behavior becomes small as shown at ③ , and then, the error of the "stay in upright position" behavior becomes small, again. The recognition system works fine only if the user operates the porter robot in the particular typical pattern.

Fig. 4. Porter Robot based on Wheeled Inverted Pendulum Mobile System

The data for the template corresponding to the user intention by recognition of the user intention based on the typical sequence of the sensor outputs and motor inputs are shown in Fig. 8. The data are collected throughout 13 trials. The motion templates $(\boldsymbol{\mu}_t, \boldsymbol{\sigma}_t)$ is calculated with the data. They are shown in the Fig.9.

Fig.7 shows the recognition results while the user operates the porter robot. While the porter robot stays in upright position, the similarity of the "stay in upright position" behavior is significantly higher than the others. When the user starts to pull the porter robot at time 3.3 [s], the similarity of the "stay in upright position" behavior becomes smaller and the one of the "start pulling" behavior becomes higher instead, as shown at ①. While the user keeps pulling the porter robot, the similarity of "keep pulling" behavior becomes small as shown at ②. When the user pull back the porter robot to make it stay in upright position, the similarity of "returning in upright position" behavior becomes significantly high as shown at ③ , and then, the one of the "stay in upright position" behavior becomes high, again.

Figs.10 and 11 show the porter robot behaviors based on/without user intention recognition. The picture sequence in Fig.10 shows the behavior based on user intention recognition. The user starts pulling the robot at (a), continues the pulling at (b), (c), and (d), then, stops at (e). The porter robot changes the desired posture angle and the control gain corresponding to the wheel angular velocity at (b) in order to follow the user intention. The porter robot does not overtake the user while the user pulling the robot and this leads the user to pull it comfortably. When the user stops walking at (e), the robot changes the control parameters for standing in upright position, again, then, it stays at the position by itself.

The picture sequence in Fig.11 shows the behavior without user intention recognition. It does not change the desired posture angle or the control gain corresponding to the wheel angular velocity. After the user starts pulling the handle of the porter robot, it accelerates the velocity and overtakes the user at (c) and (d). The behavior does not follow the intention of the user and he feels uncomfortable while he is pulling the robot.

VI. Conclusions

This paper proposed a user intention recognition system for a porter robot based on wheeled inverted pendulum mobile system. It recognizes four behaviors of the user, leaving the robot standing, starting to pull the robot, continuing the pulling, and returning the robot in upright position, in real time. The robot changes the desired posture angle and the control gain corresponding to the desired wheel angle velocity according to the behavior of the user in order to make it comfortable for the user. Experimental results showed the validity of the proposed recognition system.

As one of future work, the motion template should be updated while the user operates the porter robot in order to recognize or predict the human intention/behavior precisely. Learning the control parameters, e.g., the desired posture angle and the control gains, is another future work because one user has different preference of the port assistance from the other.

References

[1] S. Ha, Y. Yuta, "Trajectory tracking control for navigation of self-contained mobileinverse pendulum," in *Proceedings of the IEEE/RSJ/GI International Conference on Intelligent Robots and Systems '94*, vol. 3, 1994, pp. 1875–1882.

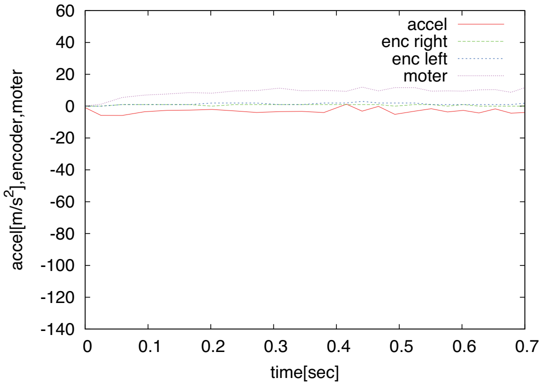
[2] B. Browning, J. Searock, P. E. Rybski, and M. Veloso, "Turning segways into soccer robots," *Industrial Robot: An International Journal*, vol. 32, no. 2, pp. 149 – 156, 2005.

[3] T. Takei, R. Imamura, , and S. Yuta, "Baggage transportation and navigation by a wheeled inverted pendulum mobile robot," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 10, pp. 3985–3994, October 2009.

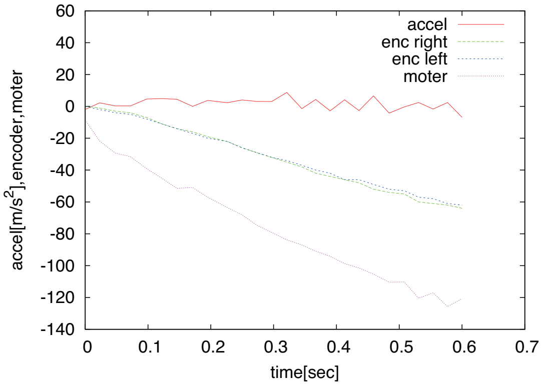
[4] M.Iribe, R.Dasai, G.Endo, T.Takubo, T.Kinugasa, and K.Osuka, "Study on a practical robotic follower to support home oxygen therapy patients - prototype cart development applying the inverted pendulum control - ," in *Proceedings of 2012 IEEE International Conference on Robotics and Biomimetics (ROBIO 2012)*, December 2012, pp. 1230–1235.

[5] T. Takeda, Y. Hirata, and K. Kosuge, "Hmm-based error recovery of dance step selection for dance partner robot," *2007 IEEE International Conference on Robotics and Automation*, pp. 1768–1773, April.2007.

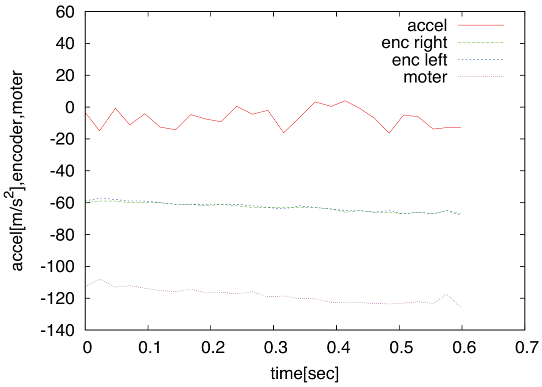
[6] ——, "Dance step estimation method based on hmm for dance partner robot," *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS*, vol. 54, no. 2, pp. 699–706, April.2007.



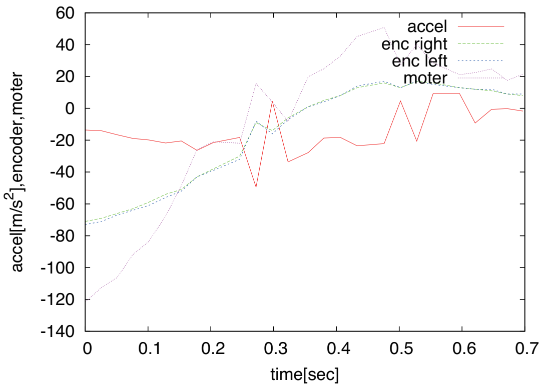
(a) Stand in upright position



(b) Start pulling

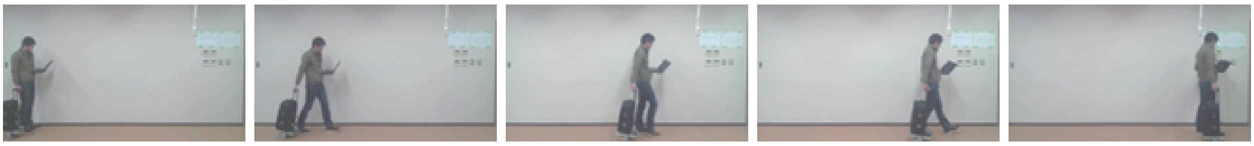


(c) Continue pulling



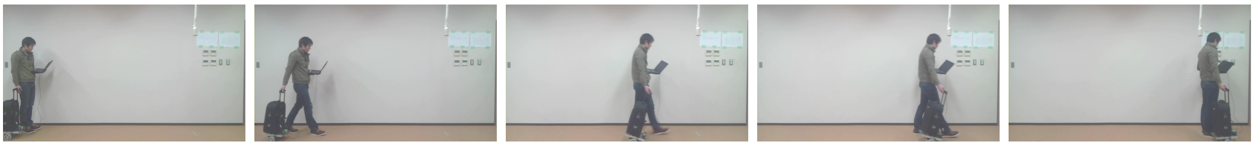
(d) Return in upright position

Fig. 5. A typical sequence of sensor outputs and motor inputs corresponding to the four behaviors



(a) (b) (c) (d) (e)

Fig. 10. Porter robot behavior based on user intention recognition and adaptive change of control parameters



(a) (b) (c) (d) (e)

Fig. 11. Porter robot behavior without user intention recognition nor adaptive change of control parameters

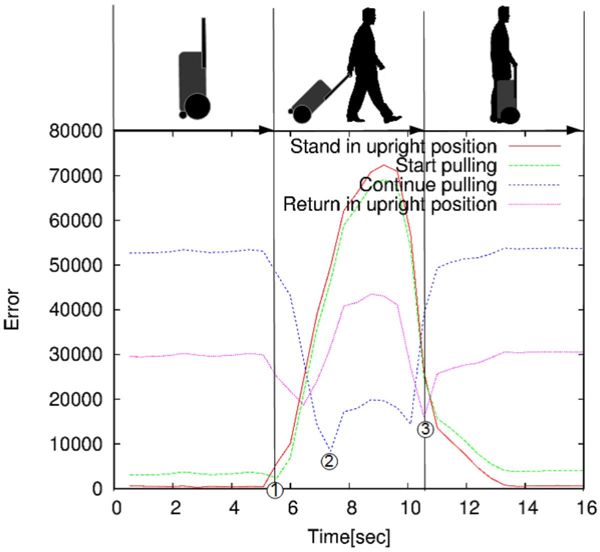


Fig. 6. Mean square error based user intention recognition results while the user starts pulling the robot, continues the pulling, and returns the robot in upright position

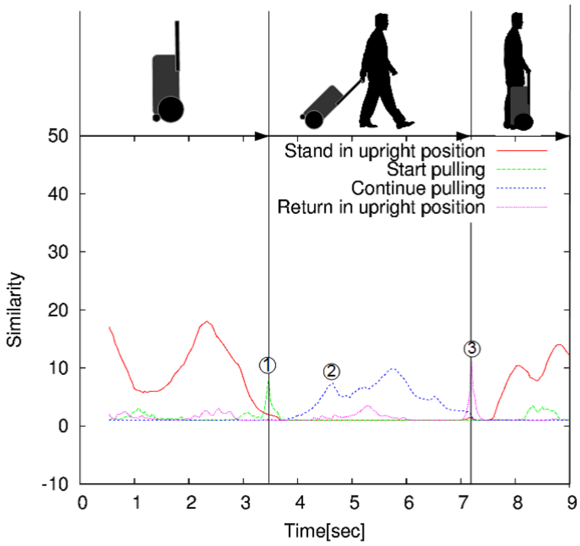
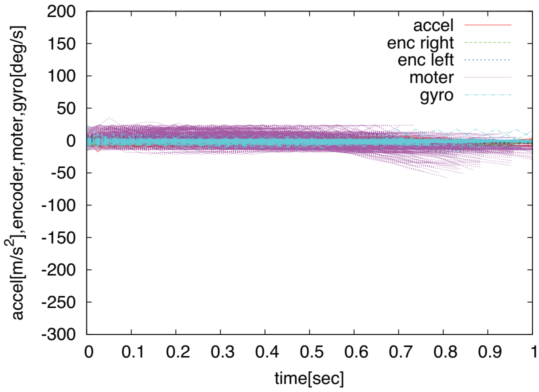
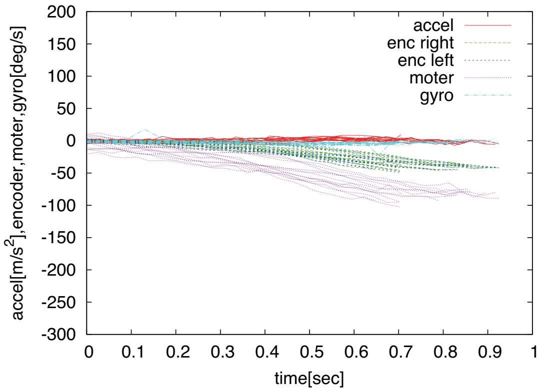


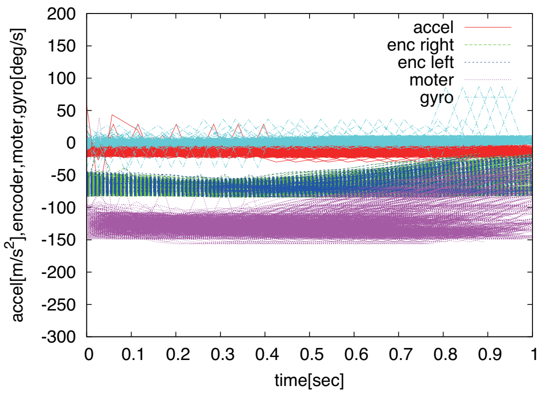
Fig. 7. User intention recognition results while the user starts pulling the robot, continues the pulling, and returns the robot in upright position



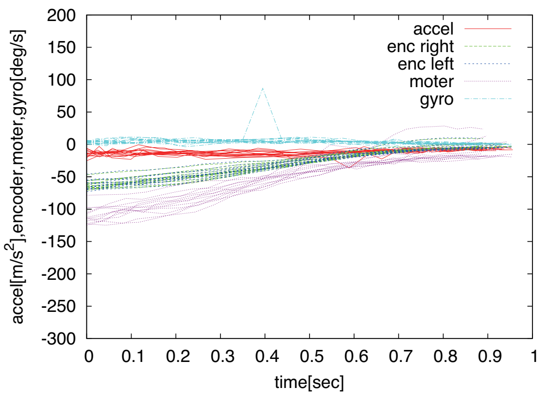
(a) Stand in upright position



(b) Start pulling

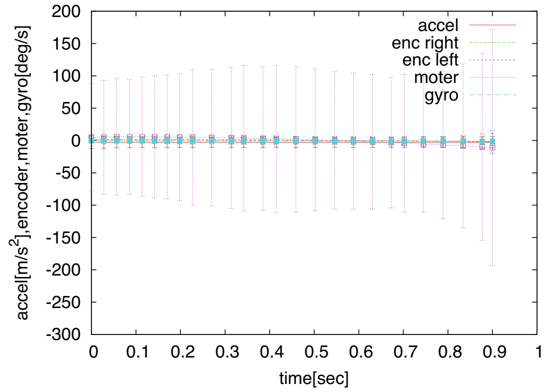


(c) Continue pulling

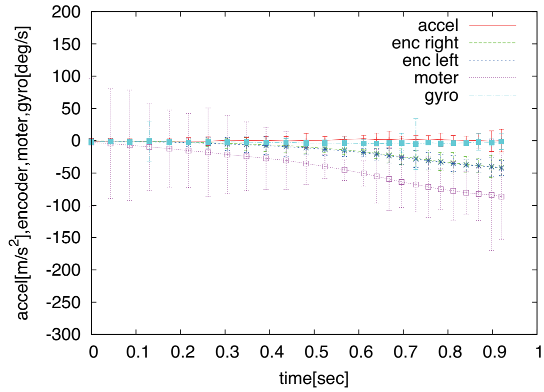


(d) Return in upright position

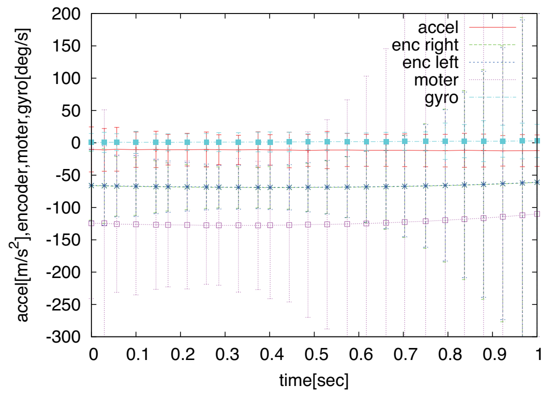
Fig. 8. Data sequence of sensor outputs and motor inputs corresponding to the four behaviors



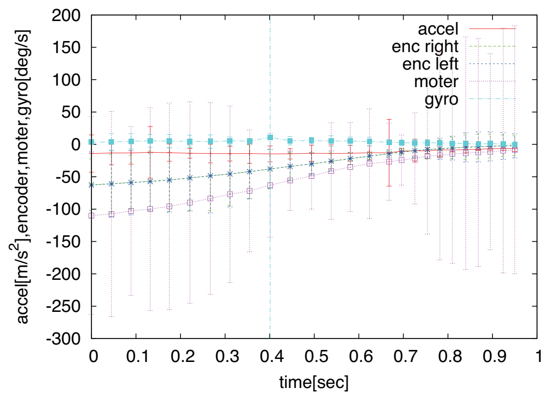
(a) Stand in upright position



(b) Start pulling



(c) Continue pulling



(d) Return in upright position

Fig. 9. Motion Template of sensor outputs and motor inputs corresponding to the four behaviors