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Live Displacement Estimation for Rough Terrain Mobile Robot: BART LAB Rescue Robot

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***Abstract*— This paper illustrates a sensorless based live displacement estimation (LDE) method for rescue robot manuevering in an unknown environment. Live displacement estimation is crucial at the instance when a heavy load is encountered as a disturbance on its path, which requires the pushing motion to alleviate the problem. This paper focuses on a pushing task, where a rescue robot pushes an object so that it can follow a path without sliding it away. Pushing is also mechanically unstable, and thus various control problems arise. Consequently, the successful completion of a pushing manipulation task requires planning. Therefore, for successful pushing operation of an object in an unknown environment it requires the precise estimation of the live displacement. LDE estimates the position and the estimated torque using the varying inertia observer (VIO), which is a variant of Disturbance Observer (DOB). The validity of the LDE was confirmed by a teleoperated rescue robot in various terrains.**

I. Introduction

Disasters, natural or human-made, have an enormous impact on most countries. Most of the disasters demand elaborate rescue missions. These rescue missions mostly constitute teams of humans, who are easily overwhelmed and require various levels of support. The hostility and the danger posed by the environment can physically as well as psychologically threaten the members of the rescue missions. However, the implementation of robots and intelligent systems in such a scenario has been a remarkable prospect. They are supposed to execute certain tasks such as searching the victims, mapping the environment, manipulating the environment, and providing limited medical intervention [1]. As such, numerous models of rescue robots have demonstrated effectiveness and reliability in extreme situations and intricate terrains. These situations necessitate the system to be robust and strong. During the operation, the robots generate path direction and can send numerous information from the environment to the robot operators at the stations away from the area. Rescue robot are able to perform their tasks in high-risk and dangerous places such as uneven ground or wet mud [2]. The robots general generate path direction and supply live streaming of environment to the robot operators at the control base outside of the wrecked area.

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BART LAB [3] rescue robot team has been involved with rescue robot for more than a decade and has successfully deployed a robot in different conditions including international competitions, robot testing, and even real test scenario. Figure.1 shown BART LAB Rescue performing mobility tasks with ease. BART LAB Rescue Robot consists of four independent flippers for mobility, middle tracks for moving forward-backward, and a five-degree of freedom (DOF) manipulator.

Figure 1 BART LAB Rescue robot performing during World Robot Summit 2018

The search and rescue operation can be executed effectively when a robot can search the path, collect information, and send it to the station. Normally, the disaster area contains uneven surfaces and the rescue robot is required to navigate in such terrain during the rescue operation [4]. Manipulating mobile rescue robots in such terrain with an unknown path is an arduous task. Most of the robots use specialized flippers to push through the obstacle and the manipulating arm consisting of a gripper moves the obstacles on its path. In this research, closed-loop dynamics is implemented through an appropriate robot model along with the measurement of feedback for pushing the obstacles within the unknown pathway. The control system relies entirely on the estimation of the change of acceleration along with the live displacement points. The notion of live displacement estimator (LDE) has been implemented to calculate the varying acceleration. Also, the contact point estimation is estimated through LDE while the robot is maneuvering through an unknown pathway. These estimations are conducted by LDE through torque observer which is a sensorless torque estimation method. After the estimation, the parameters are also compensated to accomplish the necessary control behavior of the rescue robot.

The notion of the pushing force regarding rough terrain has been studied extensively in wheeled robots. The studies have focused mainly on planetary rovers. In [5], the data from inertial measurement unit (IMU) is passed through a nonlinear Kalman filter for localization and the estimation of slip between the robot and the terrain. Similarly, [6]–[10] deals with the contact point and torque estimates for rough terrain rovers with wheels. In [6], multiple numbers of wheel torque is controlled independently with multiple optimization goal which varies according to the profile of the terrain. Wheel contact angle is considered as a main parameter which is estimated using extended Kalman filter and sensors such as inclinometer and wheel tachometer.

One of the factors that has substantial effect on contact force and position control of a mobile robot is the center of mass of the body. The idea of varying center of mass through the change of the wheel configuration for controlling the force distribution along the wheels has been illustrated in [7], [9]. Sufficient traction for the wheels is maintained by controlling the force distribution within the configurable wheels when the robot is maneuvering through a rough terrain. Similar control scheme using configurable wheel structure has been discussed by [10] where the wheels have self-configuration using passive suspension. With the scheme, torque is controlled in individual wheels for stability and minimum slippage of the robot. The reconfiguration scheme is conducted through active control in [11] which implements a novel contact point estimation algorithm through iterative methods for ensuring the stability of the tracked robot in rough terrain. As most of the aforementioned robots use feedback data from sensors such as IMU, tachometer, position encoder, inclinometer, [12] estimates the contact point and contact angle through visual estimation using LED light and a monocular camera. With the estimate of the contact angle, traction control is implemented based on the optimization of multiple criteria. In regards to the existing literature, most of the schemes are dependent on the physical configuration of the robots. However, this paper discusses the scheme that can be implemented in a robot independent of the physical structure using basic sensors available in motion control application.

In regards to the actuators for rescue robots, DC servo motors are widely used for their integrated structure, higher controllability, robust performance, and cost [13]. The performance of the control system within the robot has a predisposition towards locomotion and the appropriate motion control. This performance can be ensured through the application of an appropriate control system only. As such, this research is conducted as an assessment of the LDE technique for the relevance within the robotic system. The validity and the applicability of the proposed method to improve mobility were proven by performing experiments on the BART LAB rescue robot in a testing scenario.

II. Methodology

A. Advanced Actuator Control Modeling

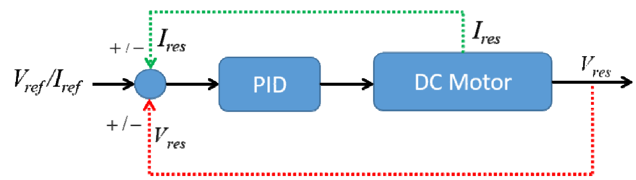


Figure 2 PID based Current/Velocity control block diagram

This section explains the rescue robot advance control modeling of the actuator which is used in this research. As stated by [14], velocity of the DC motor can be controlled through voltage. Similarly, regarding the motor torque/ force, it can be controlled with the supplied current [15]. This can be implemented through a PID based current controller with a DC motor as shown in Figure 2. This relationship can also be inferred as a relationship between the mechanical and electrical parameters of the system. However, from Figure 2, it also illustrates the role of back emf as feedback when controlling the current input.

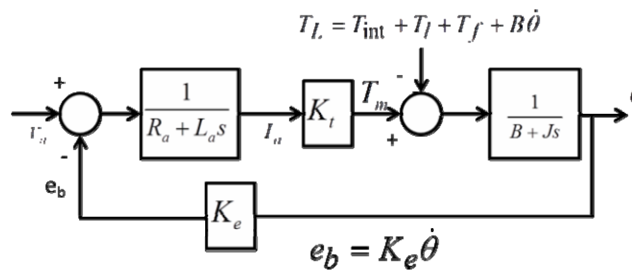


Figure 3 DC Motor control block diagram

Basically a current controller consists of a current input as well as current as the response [16]. The system in Figure 1 can be elaborated, from which the block diagram (Figure 2) and the corresponding equation 1 can be derived.

$$V_a = I_a\left(Ls + R_a + \frac{K_b K_t}{Js + B}\right) - \frac{K_b T_{dis}}{Js + B} \qquad (1)$$

Where armature resistance is represented by R_a, armature inductance by L_a, armature current by I_a, torque coefficient by K_t, moment of inertia of motor by J, back emf constant by K_b, viscous friction coefficient by B, disturbance torque by T_{dis} and armature voltage by V_a.

In Equation (2), the parameters, motor inertia (J_n) and torque constant (K_{tn}) are dependent on several attributes. Inertia is subjected primarily with the mechanical configuration and structure of the motion system. The torque coefficient depends on the rotor position of the electric motor due to irregular distribution of magnetic flux on the surface of the rotor [16], [17].

$$T_{dis} = K_{tn} I_a^{ref} - J_n \ddot{x} \quad (2)$$

Regarding disturbance torque, it consists of all internal torques, external torques, friction torques and torques due to parameter variations, which must be compensated to obtain the accurate torque estimate. The estimated disturbance torque is obtained from the velocity response and the torque current I_a. The estimation can be performed through a first-order low-pass filter as shown in Figure.4, where G_{DOB} represents the cut-off frequency of the low-pass filter. The purpose of the low-pass filter is to filter out noise arising from differentiation [18].

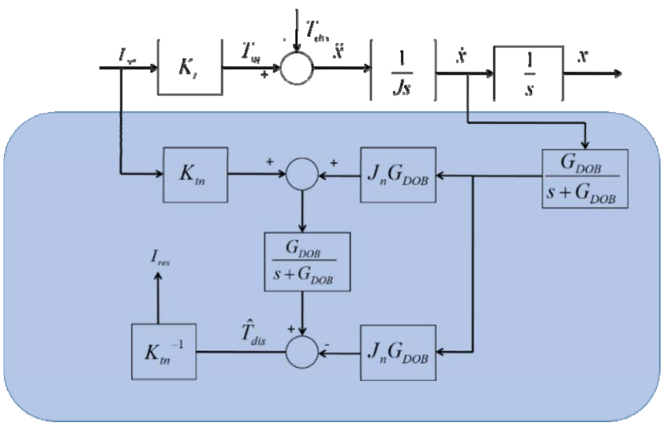


Figure 4 Disturbance Observer

The disturbance observer is used not only for disturbance compensation but also for varying inertia torque estimation. The disturbance observer is able to estimate the varying inertia without using a torque sensor by identifying the internal disturbance of the system [15] - [19]. When the motor is running with a load, the load torque exerted on the motor due to the load is obtained from (2). As shown in Fig. 5, all the disturbance components are removed at the reaction torque observer; hence, the varying inertia observer output is the estimated load torque.

$$rG_{DOB}T \leq 1 \quad (3)$$

Where r denotes the ratio between nominal inertia and actual inertia values, and T denotes the sampling time. When the rescue robot is manipulating in a terrain path the torques applied on two wheels will be different even without any disturbance. Therefore, it is important to estimate only the torque applied to the rescue robot due to the obstacles being pushed. For that, disturbance observer has also been used to the estimate reaction torque by means of a varying inertia observer (VIO) without using physical torque sensors as depicted in Figure 5 [13]. This VIO has many advantages compared with conventional torque sensors, such as higher bandwidth, accuracy and ease of use [18].

B. Live Displacement Estimator Modeling

The rescue robot navigation commands (position and orientation) were set according to a world coordinate system. Hence, the position and orientation of driven wheels must be converted into the world coordinate system data and figure 6, which represents the operation control model. From the above, control block M is the whole mass of the mobile robot platform and the system inertia is denoted as J_n. The dynamic behavior of the entire system is represented as in equation (4) from [20] [21]

$$M = \begin{bmatrix} \{\frac{J}{W^2} + \frac{M}{4} + \frac{J_r}{r^2}\} & \{\frac{M}{4} - \frac{J}{W^2}\} \\ \{\frac{M}{4} - \frac{J}{W^2}\} & \{\frac{J}{W^2} + \frac{M}{4} + \frac{J_r}{r^2}\} \end{bmatrix} \quad (4)$$

Where, J-System inertia; J_r-Inertia of the right wheel of the mobile robot platform; W-Distance between two wheels of the mobile robot platform

From [12] and also from the Figure 5 it represents the Jacobean and inverse Jacobean for both forward and inverse kinematic model. The mobile rescue robot position and orientation with respect towards its attitude angle is measured by using the directional dead reckoning. To design the live displacement estimator, the robot position and orientation feedbacks and the previously calculated position and orientation with respect towards its attitude angle is necessary.

$$x_k = x_{k-1} + V_{p,k} . cos\left(\frac{\emptyset_k + \emptyset_{k-1}}{2}\right)\Delta t \quad (5)$$

$$y_k = y_{k-1} + V_{p,k} . sin\left(\frac{\emptyset_k + \emptyset_{k-1}}{2}\right)\Delta t \quad (6)$$

Where, V_p is the speed of the robot, Δt is the sampling time, (x_k, y_k) are current positions, and (x_{k-1}, y_{k-1}) the past positions. The attitude angle is estimated using the encoder outputs which is attached with the robot wheels. The live displacement estimator is intended to evaluate the position of contact of the object in the robot. Rate feedbacks to LDE are the command and real motion of the two wheels of the robot separately when robot is in contact with obstacles.

During the period of maneuvering, the real torque and command torque compare each other and estimated value can be obtained. The overall control block as shown in figure 8. The load torque on the two wheels will be different when robot is traversing through the terrain surface. Therefore, the torque from the disturbance observer and inertia variation observer is in time varying order. The required command position and orientation are calculated at the estimator as shown in figure 8.

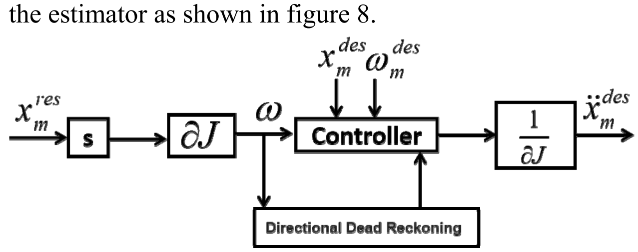


Figure 5 Kinematic Model

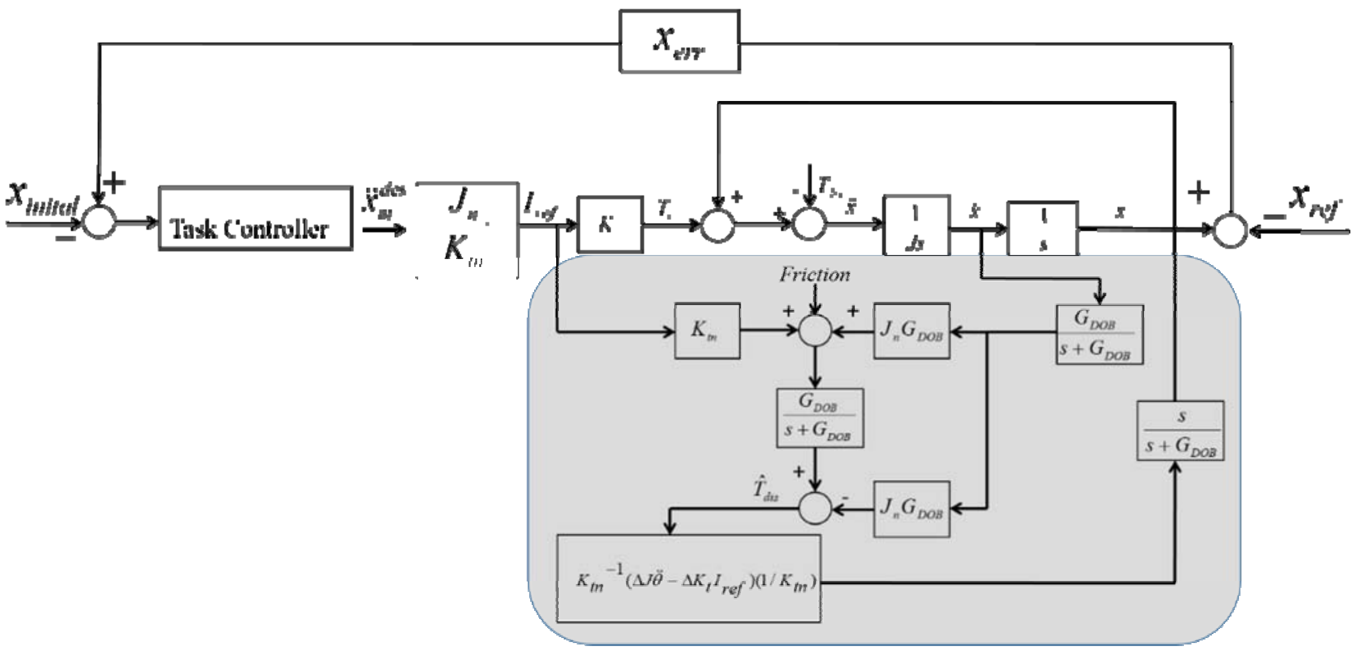


Figure 6 Disturbance observer in cooperated a varying inertia observer (VIO)

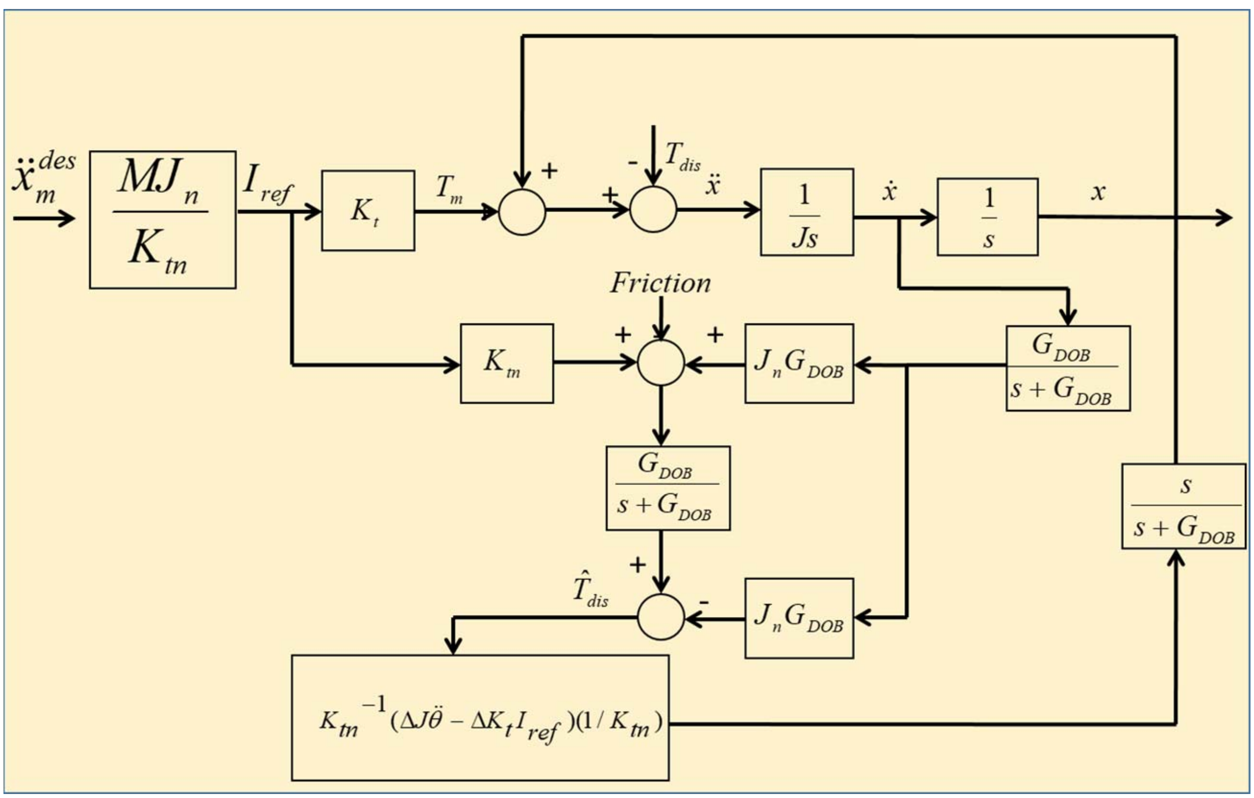


Figure 7 Dynamic control operation model

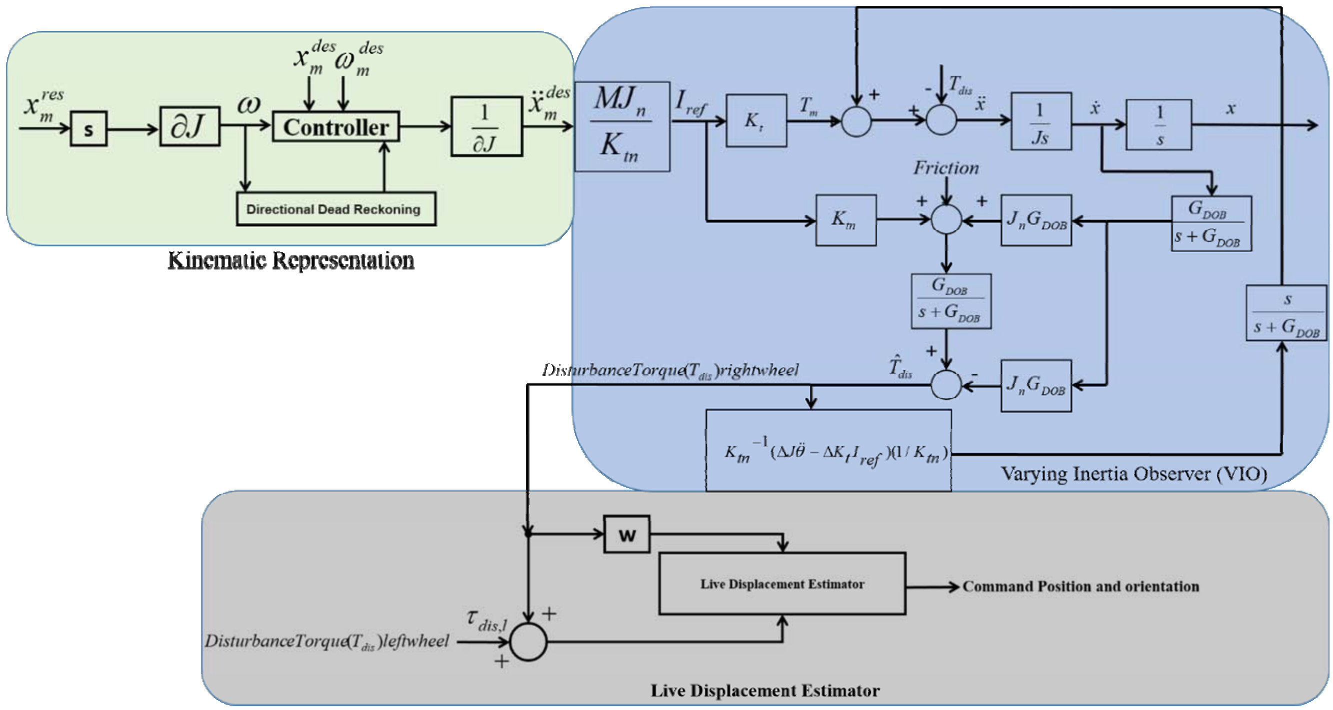


Figure 8 Overall Block Diagram

III. Simulation Results

Results of a simulation in MATLAB for a live displacement estimation are shown below. Here the distance between the wheels of the robot (w) is taken as 46 cm and mass of the whole robot including manipulator is 75 kg.

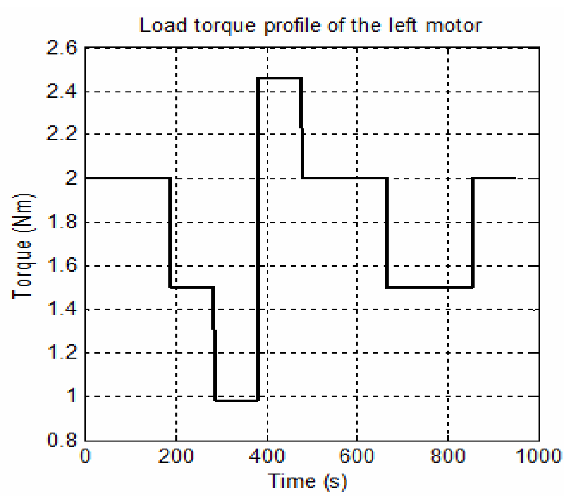


Figure 9 Load torque for left motor

Left and right wheel load torque profiles are given as for the Figure 9 and Figure 10. The point of contact of the object being pushed during navigation is estimated as for the equation (4). The estimated point is shown in Figure 11 as for the LDE. Figure 12 shows the results for the motion feedback control of the robot to manipulate in a pre-defined path.

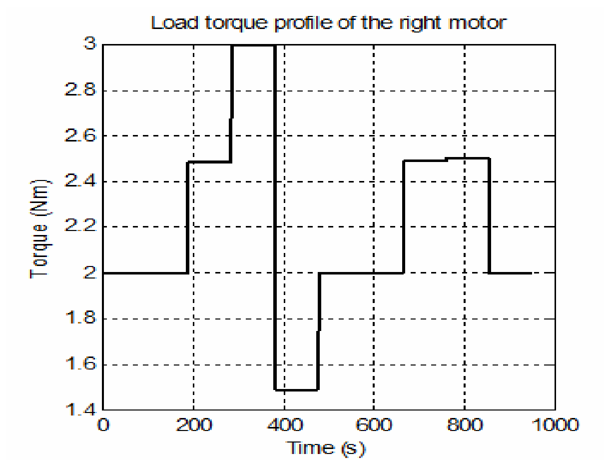


Figure 10 Load torque for right motor

IV. Conclusion

In this paper the concept of live distance estimation has been delineated along with the implementation of the concept within the model of the rescue robot. Along with that, the method has also been mentioned which can estimate the point of contact of the mobile rescue robot with the terrain during pushing motion. The validity of the concept is verified using the simulation and future implication would be to verify the system experimentally in the physical model. Figure 12 corroborate the efficacy of the system as the estimation system closely followed the intended trajectory of the motion. This even strengthens the validity of torque estimator and VIA, portraying this control system as one of the promising solutions for this class of robots.

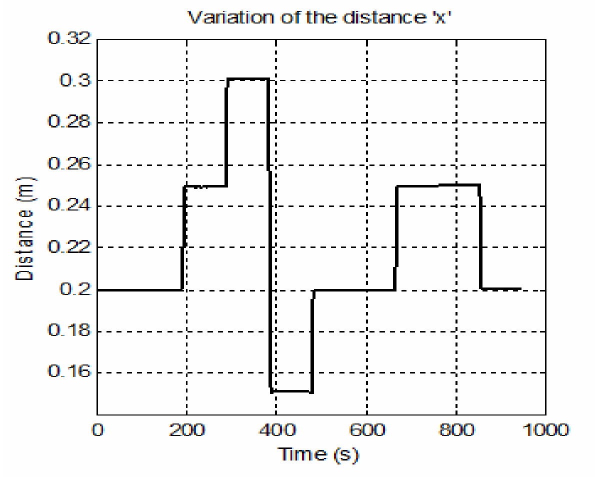
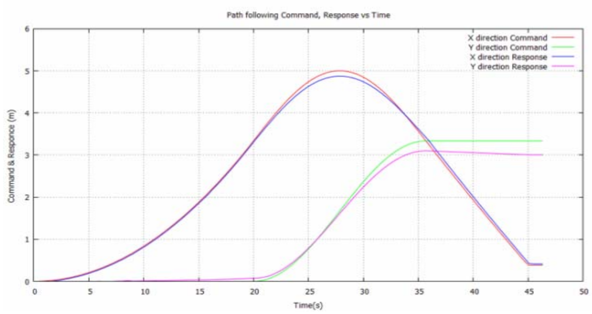
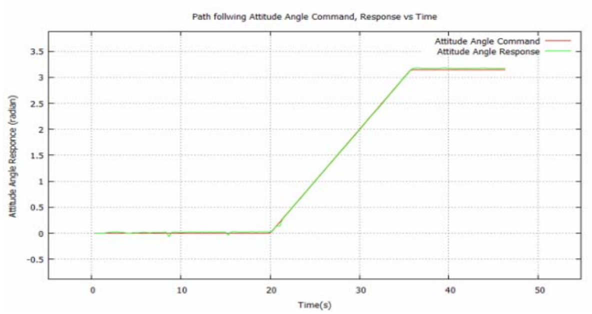


Figure 11 Variation of the Distance X



(a)



(b)

Figure 12 (a) Attitude angle – command, response vs time (b) X and Y coordinate – command, response vs time

REFERENCES

[1] R. R. Murphy et al., “Search and Rescue Robotics,” in Springer Handbook of Robotics, B. Siciliano and O. and Khatib, Eds. Berlin: Springer Berlin Heidelberg, 2006, pp. 1151–1173.

[2] H. Okada, T. Iwamoto and K. Shibuya, "Water-Rescue Robot Vehicle with Variably Configured Segmented Wheels" Journal of Robotics and Mechatronics, Vol.18, No.3, 2006, pp.278-285.

[3] J. Suthakorn, *S.S.H. Shah*, S. Jantarajit, W. Onprasert and W. Saensupo, S. Saeung, S. Nakdhamabhorn,V. Sa-Ing, and S. Reaungamornrat, "On the Design and Development of A Rough Terrain Robot for Rescue Missions", Proceedings of the 2008 IEEE International Conference on Robotics and Biomimetics Bangkok, Thailand, February 21 - 26, 2009.

[4] M. J. Micire, “Evolution and Field Performance of a Rescue Robot,” J. F. Robot., vol. 33, no. 1, pp. 17–30, 2014.

[5] J. Yi, J. Zhang, D. Song, and S. Jayasuriya, “IMU-based localization and slip estimation for skid-steered mobile robots,” *IEEE Int. Conf. Intell. Robot. Syst.*, pp. 2845–2850, 2007.

[6] K. Iagnemma and S. Dubowsky, “Traction control of wheeled robotic vehicles in rough terrain with application to planetary rovers,” *Int. J. Rob. Res.*, vol. 23, no. 10–11, pp. 1029–1040, 2004.

[7] S. V. Sreenivasan and B. H. Wilcox, “Stability and traction control of an actively actuated micro□rover,” *J. Robot. Syst.*, vol. 11, no. 6, pp. 487–502, 1994.

[8] P. Lamon, A. Krebs, M. Lauria, R. Siegwart, and S. Shooter, “Wheel torque control for a rough terrain rover,” *Proc. - IEEE Int. Conf. Robot. Autom.*, vol. 2004, no. 5, pp. 4682–4687, 2004.

[9] K. Iagnemma, H. Shibly, and S. Dubowsky, “On-line terrain parameter estimation for planetary rovers,” *Proc. - IEEE Int. Conf. Robot. Autom.*, vol. 3, no. May, pp. 3142–3147, 2002.

[10] M. Lauria, Y. Piguet, and R. Siegwart, “Octopus: an autonomous wheeled climbing robot,” *5th Int. Conf. Climbing Walk. Robot.*, pp. 315–322, 2002.

[11] M. Brunner, T. Fiolka, D. Schulz, and C. M. Schlick, “Design and comparative evaluation of an iterative contact point estimation method for static stability estimation of mobile actively reconfigurable robots,” *Rob. Auton. Syst.*, vol. 63, no. P1, pp. 89–107, 2015.

[12] H. Xu, X. Liu, H. Fu, B. B. Putra, and L. He, “Visual contact angle estimation and traction control for mobile robot in rough-terrain,” *J. Intell. Robot. Syst. Theory Appl.*, vol. 74, no. 3–4, pp. 985–997, 2014.

[13] B. M. Pillai and J. Suthakorn, “Challenges for novice developers in rough terrain rescue robots: A survey on motion control systems,” J. Control Sci. Eng., vol. 2019, 2019.

[14] Ohishi, Kiyoshi; Nakao, Masato; Ohnishi, Kouhei; Miyachi, Kunio;,"Microprocessor-Controlled DC Motor for Load-Insensitive Position Servo System," Industrial Electronics, IEEE Transactions on , vol.IE- 34, no.1, pp.44-49, Feb. 1987.

[15] K. Ohnishi, M. Shibata, T. Murakami: “Motion control for advanced mechatronics,” Mechatronics, IEEE/ASME Transactions on, vol.1, no.1pp.56-67, Mar 1996.

[16] B. M. Pillai and J. Suthakorn, “Motion control applications: Observer based DC motor parameters estimation for novices,” *Int. J. Power Electron. Drive Syst.*, vol. 10, no. 1, pp. 195–210, 2019.

[17] B. M. Pillai, S. Nakdhamabhorn, K. Borvorntanajanya, and J. Suthakorn, “Enforced acceleration control for DC actuated rescue robot,” *Proc. - 2016 22nd Int. Conf. Electr. Mach. ICEM 2016*, pp. 2640–2648, 2016.

[18] Godler, H. Honda, and K. Ohnishi, “Design guidelines for disturbance observer’s filter in discrete time,” in Proc. IEEE Int. Workshop Advanced Motion Control, 2002, pp. 390–395.

[19] T. Murakami, F. Yu, and K. Ohnishi, “Torque sensorless control in multidegree-of-freedom manipulator,” IEEE Trans. Ind. Electron., vol. 40, no. 2, pp. 259–265, Apr. 1993.

[20] S. Katsura, Y. Matsumoto, and K. Ohnishi, “Analysis and experimental validation of force bandwidth for force control,” IEEE Trans. Ind. Electron., vol. 53, no. 3, pp. 922–928, Jun. 2006.

[21] H.A.N.D. Dayarathna, L.L.G. Prabuddha, K.L.D.N.J. Ariyawansha, M.K.C.D. Chinthaka, A.M.H.S. Abeykoon, M.B.Pillai, “Sensorless contact position estimation of a mobile robot in pushing motion”, In:IEEE International Conference Circuits, Power and Computing Technologies,India,2013.p.344-49.