Fault Tolerant Control for a 4-Wheel Skid Steering Mobile Robot

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Abstract

This paper studies a fault tolerant control strategy for a four wheel skid steering mobile robot (SSMR). Through this work the fault diagnosis procedure is accomplished using structural analysis technique while fault accommodation is based on a Recursive Least Squares (RLS) approximation. The goal is to detect faults as early as possible and recalculate command inputs in order to achieve fault tolerance, which means that despites the faults occurrences the system is able to recover its original task with the same or degraded performance. Fault tolerance can be considered that it is constituted by two basic tasks, fault diagnosis and control redesign. In our research using the diagnosis approach presented in our previous work we addressed mainly to the second task proposing a framework for fault tolerant control, which allows retaining acceptable performance under systems faults. In order to prove the efficacy of the proposed method, an experimental procedure was carried out using a Pioneer 3-AT mobile robot.

1 Introduction

The higher demands to achieve more reliable performance in modern robotic systems have necessitated the development of appropriate fault diagnosis methods. The appearance of faults is inevitable in all systems, such as wheeled robots, either because their elements are worn out or because the environment in which they operate, presents unanticipated situations [4].

In a large number of applications, as for example search and rescue, planetary exploration, nuclear waste cleanup or mine decommissioning, the wheeled robots operate in environments where human intervention can be very costly, slow or even impossible. They can move freely in such dynamic environments. It is therefore essential for the robots to monitor their behavior so that faults may be addressed before they result in catastrophic failures.

A wheeled mobile robot is usually an embedded control platform, which consists of an on-board computer, power, motor control system, communications, sonars, cameras, laser radar system and sensors such as gyroscope, encoders, accelerometers etc, Fig. 1.

Figure 1. 4-Wheel Skid Steering Mobile Robot.

Fault diagnosis and accommodation for wheeled mobile robots is a complex problem due to the large number of faults that can be present such as faults of sensors and actuators [10] - [20].

Model based fault detection and isolation is a method to perform fault diagnosis using a certain model of the system. The goal is to detect faults as early as possible in order to provide a timely warning [8]. The aim of timely handling the fault occurrence is to accommodate their consequences so that the system remains functional. This can be achieved with fault tolerance.

In cases where fault could not be tolerated, it is necessary to use redundant hardware. In practice there exist two different approaches for fault tolerance control, static redundancy and dynamic redundancy [8].

In [10] and [16], the research is focused only on the problem of fault detection and identification in a mobile robot and different approaches related to state estimation were introduced. In [9] and [15], the research interest is focused only on the problem of fault detection which is a separate problem in the fault diagnosis domain. The research efforts in [7] and [12] – [14] are primarily intended to detect faults in the sensors of a wheeled robot. Concerning the research area of detection and accommodation on wheeled robots there is also a small number of efforts [18] with different approaches and methodologies.

As a fault, it can be considered any unpermitted deviation from the normal behavior of a system. Fault diagnosis is the procedure of determination of the component which is faulty. Consequently, the aim of fault diagnosis is to produce the suitable fault statement regarding the malfunction of a wheeled robot.

Fault diagnosis includes fault detection, which is the indication that something is going wrong in the system and fault isolation, which is the determination of the magnitude of the fault, by evaluating symptoms. Follows fault detection. Fault detection and isolation tasks together are referred to as fault diagnosis (FDI - Fault Detection and Isolation).

Among the various methods in the design of a residual generator, only few deal with nonlinear systems. Structural analysis is a technique that provides feasible solutions to the residual generation of nonlinear systems

Structural analysis methods are used in research publications [2] and [6]. Paper [3] presents a structural analysis for complex systems such as a ship propulsion benchmark. In [13] and [14] the authors discusses how structural analysis technique is applied to an unmanned ground vehicle for residual generation.

In this research, a model based fault diagnosis for a four wheel skid steering mobile robot (SSMR) is presented. The basic idea is to use structural analysis based technique in order to generate residuals. For this purpose we use the kinematic model of the mobile robot that serves to the design of the structural model of the system. This technique provides the parity equations which can be used as residual generators. The advantage of the proposed method is that offers feasible solution to the residual generation of nonlinear systems. Additionally, we a propose a fault accommodation technique based on RLS approximation in order to provide recalculated control inputs in the case that the left or right set of the robot tires becomes flat.

The mobile robot is supposed to be equipped with two high resolution optical quadrature shaft encoders mounted on reversible-DC motors which provide rotational speeds of the left and right wheels ω_L and ω_R respectively and an inertial measurement unit (IMU) which provides the forward linear acceleration and the angular velocity well as the angle θ between the mobile robot axle and the x axis of the mobile robot. The absolute pose (horizontal position and orientation) of the robot is available via a camera system mounted on the workspace of the robot. A distinctive marker is place at the top side of the robot.

The paper is organized as follows. We start by presenting the mathematical model of a Pioneer 3-AT mobile robot in section 2. Section 3 describes the fault diagnosis procedure. Section 4 describes the methodology of fault accommodation. In section 5 we present the application results of the proposed method to the robotic platform. Conclusions and directions for future work are presented in Section 6.

2 Mathematical Model of Pioneer 3-AT Mobile Robot

In this work, the mobile robot Pioneer 3-AT was used as a robotic platform. This robot is a four wheel skid – steering vehicle actuated by two motors, one for the left sided wheels and the other for the right sided wheels. The wheels on the same side are mechanically coupled and thus have the same velocity. Also, they are equipped with encoders and the angular readings are available through routine calls.

The kinematic model describes the motion constrains of the system, as well as the relationship of the sensors measurements with the system states and it is crucial for the fault diagnosis procedure.

2.1 Kinematic Model

The geometry of the robot is presented in Fig.2. To consider the model of the four wheel skid steering mobile robot (SSMR) it is assumed that the robot is placed on a plane surface where (X_I, Y_I) is the inertial reference frame and (X, Y) is a local coordinate frame fixed on the robot at its center of mass (COM). The position of the COM is (x, y) with respect to the inertial frame and ϑ is the orientation of the local coordinate frame with respect to the inertial frame.

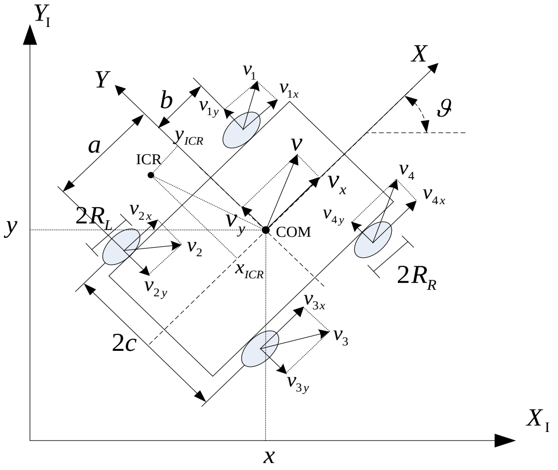

Figure 2. Mobile Robot Geometry.

As depicted in Fig. 2, *a* is the distance between the center of mass and the front wheels axle along *X*, *b* is the distance between the center of mass and the rear wheels axle along *X*, *c* is half distance between wheels along *Y* and R_L, R_R are the radii of left and right wheels respectively. The coordinates of the instantaneous center of rotation (ICR) are (x_{ICR}, y_{ICR}).

Assuming that the robot moves on a horizontal plane the linear velocity with respect to the local frame is given by

$$\boldsymbol{\upsilon} = \begin{bmatrix} \upsilon_x \\ \upsilon_y \\ 0 \end{bmatrix} \tag{1}$$

and its angular velocity is given by

$$\boldsymbol{\omega} = \begin{bmatrix} 0 \\ 0 \\ \omega \end{bmatrix} \tag{2}$$

The state vector with respect to the inertial frame is

$$\boldsymbol{q} = \begin{bmatrix} x \\ y \\ \vartheta \end{bmatrix} \tag{3}$$

The time derivatives of (3) denotes the robot's velocity vector and is given by

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\vartheta} \end{bmatrix} = \begin{bmatrix} \cos\vartheta & -\sin\vartheta & 0 \\ \sin\vartheta & \cos\vartheta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \upsilon_x \\ \upsilon_y \\ \omega \end{bmatrix} \tag{4}$$

Assuming that longitudinal slip between the wheels and the surface can be neglected we have the following equation,

$$\upsilon_{ix} = R_i \omega_i \tag{5}$$

where υ_{ix} is the longitudinal component of the total velocity vector υ_i of the i-th wheel expressed with respect to the local frame and R_i is the rolling radius of that wheel.

If we take into account all wheels (Fig. 2), the following relationships between the wheels can be obtained [11],

$$\begin{aligned} \upsilon_L &= \upsilon_{1x} = \upsilon_{2x} \\ \upsilon_R &= \upsilon_{3x} = \upsilon_{4x} \\ \upsilon_F &= \upsilon_{1y} = \upsilon_{4y} \\ \upsilon_B &= \upsilon_{2y} = \upsilon_{3y} \end{aligned} \tag{6}$$

where υ_L refers to the longitudinal coordinates of the left wheels velocities, υ_R refers to the longitudinal coordinates of the right wheels velocities, υ_F refers to the lateral coordinates of the front wheels velocities and υ_B refers to the lateral coordinates of the rear wheels velocities.

Unlike other mobile robots, lateral velocities of the four wheel skid steering mobile robot are generally nonzero since from its mechanical structure the lateral skidding is necessary if the robot changes its orientation. Therefore, in order to complete the kinematic model, the following nonholonomic constrain in Pfaffian form is introduced

$$\begin{bmatrix} -\sin\vartheta & \cos\vartheta & -x_{ICR} \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\vartheta} \end{bmatrix} = \boldsymbol{A}(\boldsymbol{q})\dot{\boldsymbol{q}} = 0 \tag{7}$$

Then we have

$$\dot{\boldsymbol{q}} = S(\boldsymbol{q})\boldsymbol{\eta} \tag{8}$$

where

$$\boldsymbol{S}(\boldsymbol{q}) = \begin{bmatrix} \cos\vartheta & x_{ICR}\sin\vartheta \\ \sin\vartheta & -x_{ICR}\cos\vartheta \\ 0 & 1 \end{bmatrix} \tag{9}$$

$$\boldsymbol{\eta} = \begin{bmatrix} \upsilon_x \\ \omega \end{bmatrix} \tag{10}$$

$\boldsymbol{S}(\boldsymbol{q})$ is a full rank matrix, whose columns are in the null space of $\boldsymbol{A}(\boldsymbol{q})$,

$$S^T(\boldsymbol{q})A^T(\boldsymbol{q}) = 0 \tag{11}$$

It is noted that since $\dim(\boldsymbol{\eta}) = 2 < \dim(\boldsymbol{q}) = 3$, equation (8) describes the kinematic of a sub-actuated robot with the nonholonomic constraint given by (7).

We suppose that the mobile robot localization is calculated via the following measurement devices:

- two high resolution optical quadrature shaft encoder mounted on reversible-DC motors which provide rotational speeds of the left and right wheels ω_L and ω_R respectively,
- an Inertial Measurement Unit (IMU) which provides the forward linear acceleration and the angular velocity as well as the angle ϑ between the mobile robot axle and the *x* axis of the mobile robot.
- A camera system, which calculates the pose of the robot, by tracking a marker placed at the top side of it.

In this work we are only interested in abrupt faults which occur in the actuators of the mobile robot and as consequence, we make the following assumptions.

- *Assumption 1:* When the mobile robot starts functioning all its components are in normal mode.
- *Assumption 2:* The magnitude of the noise is assumed to be significantly smaller than the magnitude of the faults.
- Assumption 3: Regarding the wheel radius the following inequalities are satisfied:

$$R_R + \delta R_R > 0 \quad \& \quad R_L + \delta R_L > 0$$

According to this assumption, faults that result in the complete loss of the wheel are not considered.

3 Fault Detection and Isolation

Between several techniques for generating residuals, limited number of them concerns nonlinear systems. Such one is structural analysis. Using this method we can extract information about system components that we are not able to measure. Also we can take the parity equations that allow generating residuals.

The structure of the mobile robot is described using the following sets of constrains *C* and variables *V*

$$C = \{c_1, c_2, \ldots, c_9\} \tag{12}$$

$$V = X \cup K \tag{13}$$

X is a subset of the unknown ones and *K* is a subset of known that are measurements and inputs.

The above subsets are

$$X = \{\dot{x}, \dot{y}, \dot{\vartheta}, \upsilon_x, \upsilon_y\} \tag{14}$$

$$K = \{x, y, \vartheta, \ddot{x}, \ddot{y}, \omega, \omega_L, \omega_R\} \tag{15}$$

The constrain set of the mobile robot is

$$c_1: \quad \dot{x} = \cos\vartheta\upsilon_x - \sin\vartheta\upsilon_y \tag{16}$$

$$c_2: \quad \dot{y} = \sin\vartheta\upsilon_x + \cos\vartheta\upsilon_y \tag{17}$$

$$c_3: \quad \dot{\vartheta} = \omega \tag{18}$$

$$c_4: \quad \ddot{x} = \frac{d\dot{x}}{dt} \tag{19}$$

$$c_5: \quad \ddot{y} = \frac{d\dot{y}}{dt} \tag{20}$$

$$c_6: \quad \vartheta = \int_0^t \omega d\tau \tag{21}$$

$$c_7: \quad \upsilon_x = \frac{r}{2}(\omega_R + \omega_L) \tag{22}$$

$$c_8: \quad \dot{x} = \frac{dx}{dt} \tag{23}$$

$$c_9: \quad \dot{y} = \frac{dy}{dt} \tag{24}$$

Through the above technique we create the following incidence matrix that describes the robot structure, Table 1.

Table 1. Incidence Matrix

	KNOWN								UNKNOWN				
	x	y	θ	$\ddot{x}$	$\ddot{y}$	ω	ω_L	ω_R	$\dot{x}$	$\dot{y}$	$\dot{\vartheta}$	υ_x	υ_y
c_1			1						1			1	①
c_2			1							①		1	1
c_3						1					①		
c_4				1					①				
c_5					1					1			
c_6			1								1		
c_7							1	1				①	
c_8	1								1				
c_9		1								1			

Applying matching algorithm [1] to the incidence matrix, we take out the following matched M and unmatched U constrains

$$M = \{c_1, c_2, c_3, c_4, c_7\} \tag{25}$$

$$U = \{c_5, c_6, c_8, c_9\} \tag{26}$$

In order to have residual generators we use the following parity equations

$$c_5(\dot{y}, \ddot{y}) = 0 \tag{27}$$

$$c_6(\vartheta, \dot{\vartheta}) = 0 \tag{28}$$

$$c_8(x, \dot{x}) = 0 \tag{29}$$

$$c_9(y, \dot{y}) = 0 \tag{30}$$

By starting from the unknown variables through backtracking to known variables, the residuals are:

$$r_1 = \ddot{y} - \frac{d}{dt}\left(\sin\vartheta \frac{r}{2}(\omega_R + \omega_L) + \cos\vartheta \frac{\left(\cos\vartheta \frac{r}{2}(\omega_R + \omega_L) - \int \ddot{x} d\tau \right)}{\sin\vartheta} \right) \tag{31}$$

$$r_2 = \vartheta - \int_0^t \omega d\tau \tag{32}$$

$$r_3 = \int \ddot{x} d\tau - \frac{dx}{dt} \tag{33}$$

$$r_4 = \int \ddot{y} d\tau - \frac{dy}{dt} \tag{34}$$

4 Fault Accommodation

Fault accommodation is the phase that follows the fault diagnosis. One of the most important issues to consider for the design of fault tolerant control is relative to the performance and functionality of the system under consideration. More specific it should take into consideration, the degree of performance degradation that is acceptable. There are two aspects of system performance, dynamic and steady state. In our approach we take into account the second one. We also use the aforementioned fault diagnosis method to monitor the system. The goal is to have the necessary information about the fault occurrence for timely counteraction. Figure 3 shows the overall structure of the proposed fault tolerant mechanism. It consists of two parts: i) the fault detection module which accepts as inputs the measurement of the linear and angular velocity of the SSMR and decides about the type of fault according to the method described in Section 3, and ii) the fault accommodation module which accepts as inputs the type of fault as well as the measurement of the linear and angular velocity and recalculates accordingly the command inputs in order to compensate for the fault.

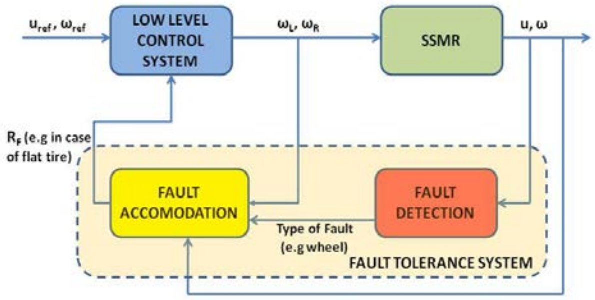

Figure 3. Fault Tolerance System Architecture.

When a fault occurs the appropriate action is undertaken (e.g. maintenance, repair, reconfiguration, stop operation) in such a way to prevent system failures. In that level the performance degradation that is acceptable is relative to the minimum requirements that ensure the system functionality. There is always the case that the malfunction may cause hazard for the process or the environment, and a decision for stopping the operation is unavoidable.

In this work, we propose a fault accommodation technique which is employed when either the left or the right set of tires becomes flat during the operation of a SSMR. It is obvious that when a flat tire fault occurs, the total nominal radius R_{NOM} (rim and tire) of the fault wheel changes to R_F, where $R_F < R_{NOM}$. The proposed fault accommodation strategy relays on the online estimation of the new radius R_F, in order to correct the commanded rotational speeds of the faulty wheel and compensate for the fault which otherwise will inevitable lead the vehicle to diverge from its nominal course.

As explained in [11], the kinematic model of the SSMR can be consider equivalent with the unicycle differential drive one, mainly due to the existence of a single motor drive and a transmission belt for each set of wheels (left and right), which impose the same rotational speed for each set of wheels. According to this assumption we can safely assume that:

$$\begin{bmatrix} u_x \\ \omega \end{bmatrix} = \frac{1}{2c}\begin{bmatrix} c & c \\ -1 & 1 \end{bmatrix}\begin{bmatrix} \upsilon_L \\ \upsilon_R \end{bmatrix} \tag{35}$$

where $\upsilon_L = \omega_L R_L$, $\upsilon_R = \omega_R R_R$ are the equivalent linear velocities of the left and right wheels respectively in relation to the rotational speeds and radii. If we consider that the fault will occur only at the one set of the wheels (left or right), we may consider only the angular velocity equation for the accommodation. Thus, only the angular velocity measurement is needed. The fault accommodation is based on the online estimation of the new radius R_F employing a Recursive Least Squares algorithm. More specific, we may consider the following linear equation for the measurement of the mobile's robot body angular velocity, in case a left side fault occurs:

$$\begin{aligned} &\hat{\omega}_k - \frac{0.5}{c}\omega_R R_R = H_k \hat{R}_{F_k} + v_k \\ &H_k = H_{L_k} = -\frac{0.5}{c}\omega_L \\ &v_k \sim (0, R_k) \end{aligned} \tag{36}$$

while in the case of a right side fault:

$$\begin{aligned} &\hat{\omega}_k + \frac{0.5}{c}\omega_L R_L = H_k \hat{R}_{F_k} + v_k \\ &H_k = H_{R_k} = \frac{0.5}{c}\omega_R \\ &v_k \sim (0, R_k) \end{aligned} \tag{37}$$

Having defined the measurement model of the robot angular velocity in the body frame, we proceed to the on line estimation of the fault wheel radius employing the following Recursive Least Squares approximation algorithm:

1. Initialize the estimator:

$$\begin{aligned} &\hat{R}_{F_0} = E(R_F) = R_{L/R} \\ &P_0 = E\left(\left(R_F - \hat{R}_{F_0}\right)^2\right) \end{aligned} \tag{38}$$

where $R_{L|R}$ is the nominal radius of the left or right wheel set.

2. Obtain a new measurement ω_k, assuming that it is given by the equation (36), or (37).

3. Update the estimate $\hat{R}_{F_k}$ and the covariance P_k of the estimation error sequentially according to:

$$\begin{aligned} &K_k = P_{k-1}H_k^T\left(H_k P_{k-1} H_k^T + R_k\right)^{-1} \\ &\hat{R}_{F_k} = \hat{R}_{F_{k-1}} + K_k\left(\omega_k - H_k \hat{R}_{F_{k-1}}\right) \\ &P_k = \left(I - K_k H_k\right) P_{k-1} \end{aligned} \tag{39}$$

where ω_k is the actual measurement of the body angular velocity as delivered by the IMU sensor.

4. Using the estimated wheel radius $\hat{R}_{F_k}$ we correct the commanded wheel angular velocity as follows:

$$\omega_{L\_cor} = \frac{-2\omega_k c + \omega_R R_R}{\hat{R}_{F_k}} \tag{40}$$

$$\omega_{R\_cor} = \frac{2\omega_k c + \omega_L R_L}{\hat{R}_{F_k}} \tag{41}$$

in case there is a left or a right wheel fault respectively.

5 Application Results

The proposed method has been implemented and tested experimentally on Pioneer 3-AT mobile robot. All experiments have been performed indoors. We consider a faulty situation where the right wheel set is flat (forward and backward wheels). We apply a command of $\omega_L = \omega_R = 5\,rad/s$ for both set of wheels. In the nominal situation (no faults) the robot should move (almost) straight forwards without any deviation. The robot starts from the origin of the inertial frame and moves for 2.5m. The time interval dt between successive IMU measurements is $2.5m\sec$. The nominal radius of the wheels (proper inflation) is $R_L = R_R = 0.115\,m$.

In the first experiment (Fig. 4), the fault accommodation algorithm is not enabled and as we can observe from the trajectory of the vehicle, the SSMR significantly diverges from its nominal course to the right.

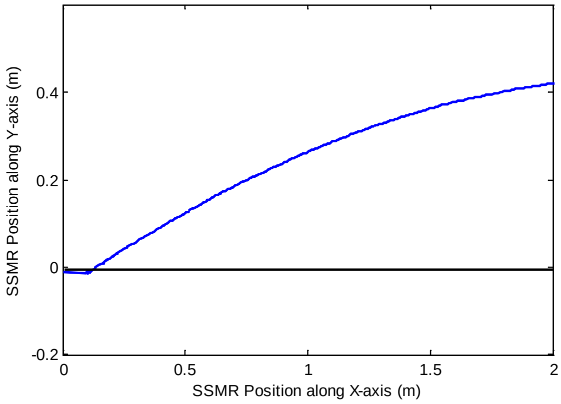

Figure 4. Robot's position while the right wheel set is flat.

The fault detection algorithm is enabled, and as we can see from Fig. 5 the fault was successfully detected by the proposed structural analysis algorithm.

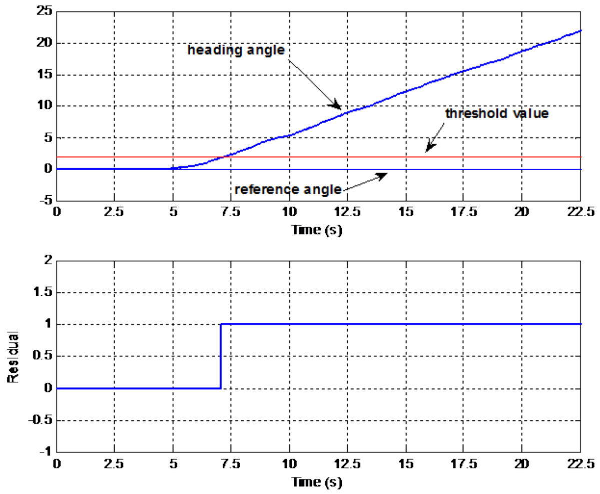

Figure 5. Fault signal as the right wheel set is flat.

In the second experiment we impose the same control inputs to the SSMR $\omega_L = \omega_R = 5\, rad/s$, but this time not only the fault detection but also the proposed fault accommodation algorithm is enabled. As we can see in Fig. 6 the on line estimation algorithm quickly converge to the new radius of the faulty wheel set and consequently the fault accommodation algorithm provides modified inputs to the right wheel set (Fig. 7).

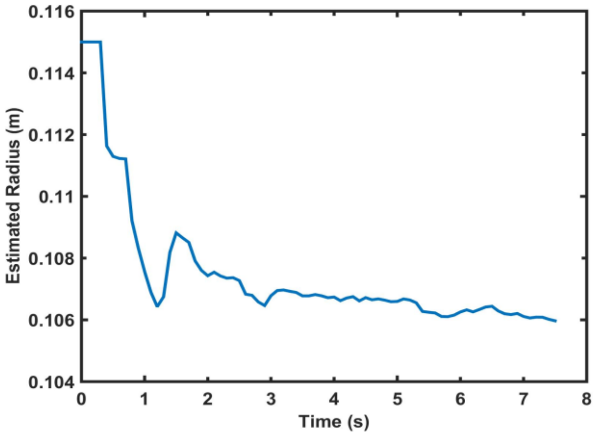

Figure 6. On line estimation of faulty radius.

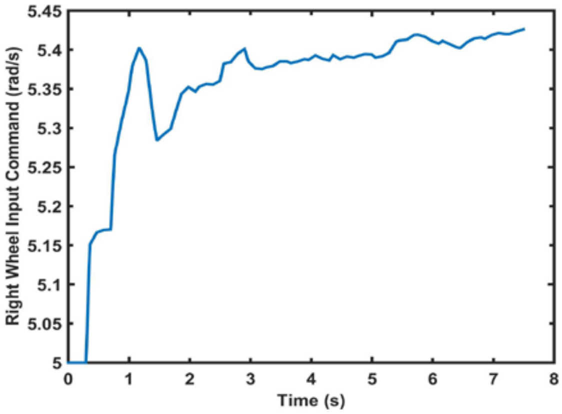

Figure 7. Recalculated input from the fault accommodation algorithm.

As we can observe from Fig. 8 the trajectory of the SSMR was successfully detained in an almost straight line form.

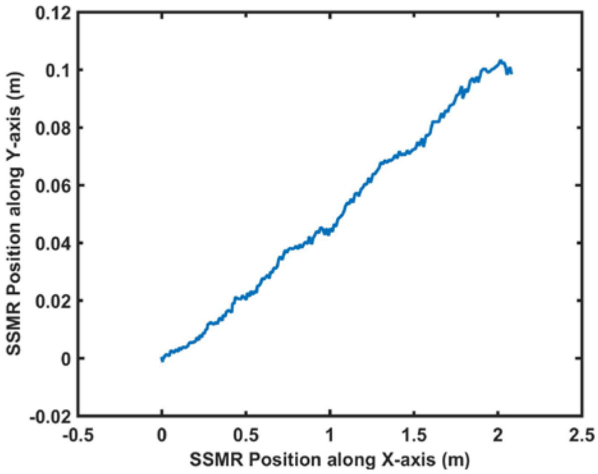

Figure 8. SSMR Corrected Planar Trajectory.

6 Conclusion

The notion of fault tolerant control for a 4-wheel skid steering mobile robot is an important problem to deal with, since faults appearance is inevitable in such systems. The most significant challenge arises from the complexity of the system. In this paper we have introduced the underlying concepts for our approach to fault tolerant control for mobile robots focusing our attention mainly to control reconfiguration. As concerning the issue of fault diagnosis the structural analysis based technique is used in order to generate residuals. We use the kinematic model of the mobile robot that serves to the development of the structural model of the system. The above technique provides the parity equations which can be used as residual generators since model based fault diagnosis approach is based on residuals. The advantage of the above method is that it can offer a feasible solution to the residual generation of nonlinear systems. The fault accommodation procedure targets in the case where one of the two wheel tire sets becomes flat. The proposed accommodation method is based on a RLS approximation of the new faulty wheel radius and via this information a new control input is calculated in order to compensate for the fault.

The efficacy of the proposed method is demonstrated through an extensive experimental procedure using a mobile robot Pioneer 3-AT.

Acknowledgments

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References

[1] M. Blanke, M. Kinnaert, J. Luzne, M. Staroswiecki, «Diagnosis and Fault Tolerant Control», ser. Heidelberg, Springer-Verlag, 2003.

[2] M. Blanke, H. Niemann, and T. Lorentzen, “Structural analysis – a case study of the Rømer satellite,” in Proc. of IFAC Safeprocess 2003, Washington, DC, USA, 2003.

[3] M. Blanke, V. Cocquempot, R. I. Zamanabadi, and M. Staroswiecki, “Residual generation for the ship benchmark using structural approach,” in Proc. of Int. Conference on CONTROL’98, Swansea, UK, Sep 1998.

[4] Steven X. Ding, “Model-based Fault Diagnosis Techniques: Design Schemes, Algorithms, and Tools, Springer-Verlag Berlin, 2008.

[5] G.K. Fourlas, K.J. Kyriakopoulos, N.J. Krikelis, “Fault Diagnosis of Hybrid Systems”, Proceedings of the 2005 IEEE International Symposium on Intelligent Control, 13th IEEE Mediterranean Conference on Control and Automation, Limassol, Cyprus, 2005.

[6] G.K. Fourlas, “Theoretical Approach of Model Based Fault Diagnosis for a 4 - Wheel Skid Steering Mobile Robot, 21st IEEE Mediterranean Conference on Control and Automation (MED '13), Platanias-Chania, Crete, GREECE, June 25-28, 2013.

[7] G. Ippoliti, S. Longhi, A. Monteriμu, “Model-based sensor fault detection system for a smart wheelchair”, IFAC 2005.

[8] R. Isermann, “Fault Diagnosis Systems – An Introduction from Fault Detection to Fault Tolerant”, Springer-Verlag Berlin Heidelberg, 2006.

[9] B. Halder, and N. Sarkar, “Robust Fault Detection of Robotic Systems: New Results and Experiments”, Proceedings of the 2006 IEEE International Conference on Robotics and Automation, Orlando, Florida - May 2006.

[10] Z. Kira, “Modeling Cross-Sensory and Sensorimotor Correlations to Detect and Localize Faults in Mobile Robots”, Proceedings of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems San Diego, CA, USA, Oct 29 - Nov 2, 2007.

[11] K. Kozlowski and D. Pazderski, “Modeling and Control of a 4-Wheel Skid-Steering Mobile Robot”, Int. J. Appl. Math, Comput. Sci., 2004, vol. 14, no. 4, 477-496.

[12] Y. Morales, E. Takeuchi and T. Tsubouchi, “Vehicle Localization in Outdoor Woodland Environments with sensor fault detection”, 2008 IEEE International Conference on Robotics and Automation, Pasadena, CA, USA, May 19-23, 2008.

[13] A. Monteriù, P. Asthan, K. Valavanis and S. Longhi, “Model-Based Sensor Fault Detection and Isolation System for Unmanned Ground Vehicles: Theoretical Aspects (part I)”, 2007 IEEE International Conference on Robotics and Automation Roma, Italy, 10-14 April 2007.

[14] A. Monteriù, P. Asthan, K. Valavanis and S. Longhi, “Model-Based Sensor Fault Detection and Isolation System for Unmanned Ground Vehicles: Experimental Validation (part II), 2007 IEEE International Conference on Robotics and Automation Roma, Italy, 10-14 April 2007.

[15] P. Sundvall and P. Jensfelt, “Fault detection for mobile robots using redundant positioning systems” Proceedings of the 2006 IEEE International Conference on Robotics and Automation, Orlando, Florida - May 2006.

[16] C. Valdivieso, and A. Cipriano, “Fault Detection and Isolation System Design for Omnidirectional Soccer-Playing Robots”, Proceedings of the 2006 IEEE Conference on Computer Aided Control Systems Design Munich, Germany, October 4-6, 2006.

[17] R. Izadi-Zamanabadi, “Structural Analysis Approach to Fault Diagnosis with Application to Fixed-wing Aircraft Motion” in Proc. of American control Conference, USA, 2002.

[18] D. Zhuo-hua, CAI Zi-xing, YU Jin-xia “Fault Diagnosis and Fault Tolerant Control for Wheeled Mobile Robots under Unknown Environments: A Survey”, Proceedings of the 2005 IEEE International Conference on Robotics and Automation, Barcelona, Spain, April 2005.

[19] S.Zaman, G. Steinbauer, J.Maurer, P.Lepej, and S.Uran, “An integrated model-based diagnosis and repair architecture for ROS-based robot systems”, IEEE International Conference on Robotics and Automation (ICRA), Karlsruhe, Germany, 2013.

[20] D. Portugal, and Rui P. Rocha, “Scalable, Fault-Tolerant and Distributed Multi-Robot Patrol in Real World Environments” 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), November 3-7, Tokyo, Japan, 2013.