MODEL-BASED SENSOR FAULT DETECTION SYSTEM FOR A SMART WHEELCHAIR

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Abstract: This paper presents a preliminary set of results on the design of a Sensor Fault Detection System (SFDS) for a smart wheelchair to prevent simples navigation sensor faults and hence to reduce the risk of safety hazards. The Structural Analysis technique is considered which uses graph theory to determine which redundancy exists in the sensory system and thus shows the possibility to detect and handle the navigation sensor faults. The considered navigation sensor equipment includes odometric, gyroscopic and laser range measures.

Keywords: Fault diagnosis, fault detection, fault isolation, wheelchair, analytical redundancy relations, structural analysis.

1. INTRODUCTION

Assistive Technology is basically the use of technology to assist an individual with physical disabilities to perform functions that may otherwise be difficult or impossible. In this context, robotics plays a major role thanks to the large number of aids it provides for the persons with disabilities (Dario *et al.*, 1996; Robinson, 1993). Many activities in this sector have been focused on telemanipulators controlled by users with disabilities and also on manipulators on board of electric wheelchairs to help the users in their work and in domestic activities (Dallaway *et al.*, 1995). In the European Union the research activities in this sector have been mainly coordinated within the TIDE initiative (TIDE, 1993). In this framework, the development of intelligent navigation systems based on sensors that are easily ported between various electric vehicles has been performed in the TIDE project SENARIO (Dallaway *et al.*, 1995; Katevas *et al.*, 1997). Another TIDE project, MOVAID (Dario, 2000), mainly focused on the development of a modular mobile robot interacting with the user by means of a friendly interface for the accomplishment of domestic tasks. In order to facilitate the integration of inputoutput devices for robotic assistive systems the TIDE project M3S (Multi Master Multi Slave) (M3S, 2000) has been developed. This allows a flexible and reliable communication among devices made by different manufacturers. Other significant research activities are those related to smart powered wheelchairs. In the developed smart wheelchairs, the autonomy and safety aspects are guaranteed by a set of sonar sensors. Different sensor devices, such as vision systems, are also used (Gomi and Griffith, 1998; Wheelesley, 1997; Yanco and Gips, 1997; Levine *et al.*, 1999).

This paper presents the design of a *Sensor Fault Detection System* (SFDS) and its integration with the navigation system for a commercial powered wheelchair. The aim is to prevent that simples navigation sensor faults develop into serious failure and hence increase the wheelchair availability and reduce the risk of safety hazards. This is accomplished applying the Structural Analysis technique which uses graph theory to determine which redundancy exist in the system and thus shows the possibility to detect and handle the navigation sensor faults. The considered sensor equipment includes odometric, gyroscopic and laser measures. The Sensor Fault Detection System provides the commercial wheelchair with a set of functions which increase the navigation reliability of the wheelchair, and thus the autonomy of elderly and people with motor disabilities.

In this paper a preliminary set of results on the design of a Sensor Fault Detection System for a smart wheelchair is introduced and discussed. In Section 2 the navigation system of a smart wheelchair will be recalled. The sensor equipment is introduced in Section 3. The designed Sensor Fault Detection System is described in Section 4. Finally, concluding remarks end the paper.

2. THE NAVIGATION SYSTEM

The design of a navigation system of a powered wheelchair has already been developed (Fioretti *et al.*, 2000) taking into account the criteria of usability, acceptability, efficiency, safety and costs.

Three different levels of autonomy of the navigation module have been developed. In the first and second level of autonomy the user interacts with the navigation system.

In the first level of autonomy, the navigation module performs a simple filtering of the user's commands and in front of a detected obstacle the module performs a *Stop + Wait* action. In the second level of autonomy, the navigation module introduces some local corrections on the user commands by a simple obstacle avoidance algorithm. The obstacle avoidance algorithm is based on a fuzzy-logic approach that represents an extension of the algorithm proposed in (Leo *et al.*, 1995). In the last level of autonomy the navigation system implements a high level of autonomy. This level is used in the modality of automatic motion control of the robotic system.

Recently, the functionalities of the smart wheelchair have been improved introducing a robotic arm and a hybrid motion control system (Bonci *et al.*, 2004) which is able to integrate the navigation module with the controller of the robotic arm. The manipulation tasks of the robotic system are achieved by using a commercial low cost robotic arm designed for assistive applications and used for manipulating objects. In the developed application, the manipulator task is imposed by the user interface based on a real or virtual joystick device. To improve the usability of this manipulator an automatic grasping procedure has been introduced. The procedure requires a low cost vision system mounted on manipulator, which is used for the 3D reconstruction of the goal object and for estimating the grasping points on the object surface. This procedure is utilized in the modality of automatic motion control that is the third level of autonomy. The object to be manipulated is chosen by the user and the automatic procedure computes the trajectory for grasping the object.

3. THE SENSOR EQUIPMENT

The considered sensors are: two incremental optical encoders in the rear wheels, an optical gyroscope (HITACHI mod. HOFG-1), and a laser range finder (SICK LMS mod. 200). These sensors are used for the on-line estimation of the vehicle pose and for detecting unknown obstacles in the environment, that is *a priori* assumed known. The pose estimation is performed by the Extended Kalman Filtering approach (Ippoliti *et al.*, 2004) which represents an efficient procedure for integrating sensors readings with the *a priori* knowledge of the environment.

The kinematic model of the considered wheelchair is equivalent to that of an unicycle-like mobile robot with two driving wheels.

3.1 Odometric measures

Consider an unicycle-like mobile robot with two driving wheels, mounted on the left and right sides of the robot, with their common axis passing through the center of the robot. Localization of this mobile robot in a two-dimensional space requires the knowledge of coordinates x and y of the midpoint between the two driving wheels and of the angle θ between the main axis of the robot and the X-direction of the considered inertial coordinate system (O, X, Y). The kinematic model of the unicycle robot is described by the following equations:

$$\dot{x}(t) = \nu(t)\cos\theta(t) \tag{1}$$

$$\dot{y}(t) = \nu(t)\sin\theta(t) \tag{2}$$

$$\dot{\theta}(t) = \omega(t) \tag{3}$$

where $\nu(t)$ and $\omega(t)$ are, respectively, the displacement and angular velocities of the robot which are expressed by:

$$\nu(t) = \frac{D}{4}\left(\omega_l\left(t\right) + \omega_r\left(t\right)\right) \tag{4}$$

$$\dot{\theta}(t) = \frac{D}{2L}\left(\omega_r\left(t\right) - \omega_l\left(t\right)\right) \tag{5}$$

where $\omega_r(t)$ and $\omega_l(t)$ are the angular velocities of the right and left wheels, respectively, D is the wheel diameter and L is the distance between the wheels.

3.2 Fiber optic gyroscope measures

The operative principle of a Fiber Optic Gyroscope (FOG) is based on the Sagnac effect. The FOG is made of a fiber optic loop, fiber optic components, a photo-detector and a semiconductor laser. The phase difference of the two light beams traveling in opposite directions around the fiber optic loop is proportional to the rate of rotation of the fiber optic loop. The rate information is internally integrated to provide the absolute measurements of orientation. A FOG does not require frequent maintenance and have a longer lifetime of the conventional mechanical gyroscopes. In a FOG the drift is also low. A complete analysis of the accuracy and performance of this internal sensor has been developed in (Borenstein and Feng, 1996; Chung *et al.*, 2001; Killian, 1994; Zhu *et al.*, 2000). This internal sensor represents a simple low cost solution for producing accurate pose estimation of a mobile robot. The FOG readings are denoted by $\theta_g(\cdot) = \theta_g^r(\cdot) + n_\theta(\cdot)$, where $\theta_g^r(\cdot)$ is the true value and $n_\theta(\cdot)$ is an independent, zero mean, gaussian white sequence $(n_\theta(\cdot) \sim N(0, \sigma_\theta^2)$.

3.3 Laser scanner measures

The distance readings by the Laser Measurement System (LMS) are related to the in-door environment model and to the configuration of the mobile robot.

Denote with l the distance between the center of the laser scanner and the origin O' of the coordinate system (O', X', Y') fixed to the mobile robot. At the sampling time t_k, the position x_s, y_s and orientation θ_s of the center of the laser scanner, referred to the inertial coordinate system (O, X, Y), have the following form:

$$x_s(t_k) = x(t_k) + l\,\cos\theta(t_k) \tag{6}$$

$$y_s(t_k) = y(t_k) + l\,\sin\theta(t_k) \tag{7}$$

$$\theta_s(t_k) = \theta(t_k) \tag{8}$$

The walls and the obstacles in an in-door environment are represented by a proper set of planes orthogonal to the plane XY of the inertial coordinate system. Each plane P is represented by the triplet P_r, P_n and P_ν, where P_r is the normal distance of the plane from the origin O, P_n is the angle between the normal line to the plane and the X-direction and P_ν is a binary variable, $P_\nu \in \{-1,\ 1\}$, which defines the face of the plane reflecting the laser beam. In such a notation, the expectation of the laser reading $d(t_k)$, relative to the present distance of the center of the laser scanner from the plane P, has the following expression (see Figure (1)):

$$d(t_k) = P_\nu \frac{P_r - x_s(t_k)\cos(P_n) - y_s(t_k)\sin(P_n)}{\cos(\theta_d)} \tag{9}$$

where $\theta_d = P_n - \theta^*$ with $\theta^* \in [\theta_0,\ \theta_1]$ given by:

$$\theta^* = \theta + \theta_s - \frac{\pi}{2} \tag{10}$$

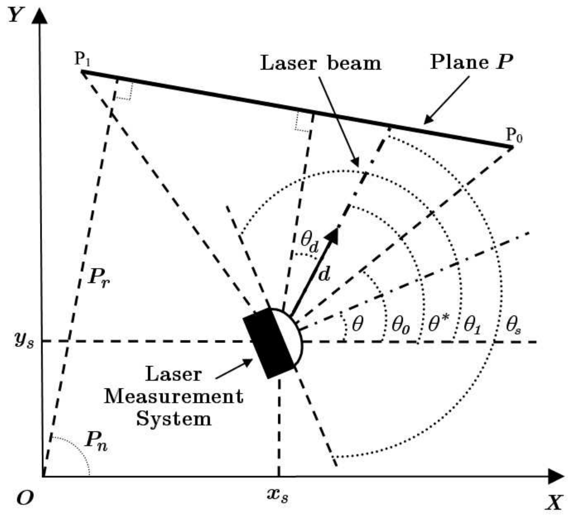

Fig. 1. Laser scanner measure.

4. SENSOR FAULT DETECTION SYSTEM

As all artificial systems controlled by the use of sensors regards also the developed smart wheelchair is vulnerable to faults such as defects in sensors or failures, which can cause undesired reactions and consequences as damage to technical parts of devices, to the user or to the environment. For this reason fault detection is an important and a key issue to consider (Blanke *et al.*, 2000).

In this section a Sensor Fault Detection System is proposed for introducing in the robotic assistive system a set of functions for increasing the navigation reliability of the wheelchair. The *fault detection* task consists of making a binary decision - either that a fault or failure is present or not. The presence of faults must be known before they become serious. Unknown disturbances and imprecise measurements, not necessarily faulty, make the task of "early fault detection" rather imprecise and difficult to achieve reliably. The fault detection is used for the *fault isolation* task where the source of the fault is determined, the sensor that has become faulty.

The combined process of *fault detection and isolation* is usually referred in the control engineering literature as the *FDI* function. A monitoring procedure which is used to detect and isolate faults and assess their significance/severity in a system is called a *fault diagnosis system* (Patton *et al.*, 2000).

The proposed Sensor Fault Detection System will be integrated with the navigation system where different levels of autonomy are implemented. Therefore, the SFDS should be adapted to the considered levels of autonomy in order to involve the user on the decision about the occurred fault. The proposed SFDS concerns of all FDI steps. If a fault is detected, sensor faults are isolated when possible by showing which sensor is faulty.

The proposed fault detection system introduces the FDI functions using two modules: a residual generation module and a residual evaluation module (also called decision module) (Blanke *et al.*, 2003*b*). The residuals are signals that, in the absence of faults, deviate from zero only due to modelling uncertainties, with nominal value being zero, or close to zero under actual working conditions. If a fault should occur, the residuals deviate from zero with a magnitude such that the faulty condition can be distinguished from the fault free working mode. In the following subsection, the structural analysis is applied to the case study.

4.1 Structural analysis: the residual generator module

The residual generator module (Blanke *et al.*, 1998) is able to generate the residuals exploiting the main ideas of the structural analysis (Blanke *et al.*, 2003*a*). The structural analysis is a set of graph based tools to explore fundamental properties of a system using structure graphs. A structure graph describes which bonds exist between variables and constraints in a system without describing these elements in details. Matching on a structure graph of a dynamic system can disclose which subset of equations provide a redundant description of the system. The matching process is essentially a way to indicate which equations (or constraints) in a nonlinear system are needed to find a solution for its variables. When there are more equations than needed, excess equations can be used to check for validity of observations. If such excess equation, unmatched constraint called residual, is not valid, this will indicate the presence of a fault in the system (Monteriù, 2003).

The model of the smart wheelchair is considered as a set of constraints (see (11)–(23)):

$$\mathcal{C} = \{c_1, c_2, \cdots, c_{13}\}$$

which are applied to a set of variables $\mathcal{Z} = \mathcal{X} \cup \mathcal{K}$, where $\mathcal{X}$ denotes the subset of the unknown variables while $\mathcal{K}$ denotes the subset of the known ones: sensor measurements, variables with known values (constants, parameters), and reference variables. The set of unknown variables is:

$$\mathcal{X} = \left\{x, y, \theta, \dot{x}, \dot{y}, \dot{\theta}, \omega, \nu, d, \omega_l, \omega_r\right\}$$

and the set of known variables is:

$$\mathcal{K} = \{y_{1,m}, y_{2,m}, y_{3,m}, y_{4,m}\}$$

The set of constraints for the smart wheelchair is:

$$c_1: \quad \dot{x} = \nu \cos\theta \tag{11}$$

$$c_2: \quad \dot{y} = \nu \sin\theta \tag{12}$$

$$c_3: \quad \dot{\theta} = \omega \tag{13}$$

$$c_4: \quad \omega_l = \frac{2}{D}\left(\nu - \frac{L}{2}\omega\right) \tag{14}$$

$$c_5: \quad \omega_r = \frac{2}{D}\left(\nu + \frac{L}{2}\omega\right) \tag{15}$$

$$c_6: \quad d = P_\nu \frac{P_r - x\cos\left(P_n\right) - y\sin\left(P_n\right)}{\cos\left(P_n - \theta - \theta_s + \frac{\pi}{2}\right)} \tag{16}$$

$$c_7: \quad \dot{x} = \frac{dx}{dt} \tag{17}$$

$$c_8: \quad \dot{y} = \frac{dy}{dt} \tag{18}$$

$$c_9: \quad \dot{\theta} = \frac{d\theta}{dt} \tag{19}$$

$$c_{10}: \quad y_{1,m} = \omega \tag{20}$$

$$c_{11}: \quad y_{2,m} = \omega_l \tag{21}$$

$$c_{12}: \quad y_{3,m} = \omega_r \tag{22}$$

$$c_{13}: \quad y_{4,m} = d \tag{23}$$

The structure is described by the following binary relation:

$$S : \mathcal{C} \times \mathcal{Z} \rightarrow \{0, 1\}$$

$$\left(c_i, z_j\right) \rightarrow \begin{cases} S\left(c_i, z_j\right) = 1 & \text{iff } c_i \text{ applies to } z_j \\ S\left(c_i, z_j\right) = 0 & \text{otherwise} \end{cases}$$

The structure of the considered system can be represented by the incidence matrix illustrated in Table 1.

Table 1. Incidence matrix.

	known				unknown										
↗	$y_{1,m}$	$y_{2,m}$	$y_{3,m}$	$y_{4,m}$	x	y	θ	$\dot{x}$	$\dot{y}$	$\dot{\theta}$	ω	ν	d	ω_l	ω_r
c_1							1	1				1			
c_2							1		1			1			
c_3										1	1				
c_4											1	1		1	
c_5											1	1			1
c_6					1	1	1						1		
c_7					1			1							
c_8						1			1						
c_9							1			1					
c_{10}	1										1				
c_{11}		1												1	
c_{12}			1												1
c_{13}				1									1		

The matching algorithm identifies the over-determined parts of the system (Blanke *et al.*, 1998).

The result is lists of the matched and unmatched constraints. The matched constraints result:

$$\mathcal{M} = \{c_1, c_2, c_3, c_5, c_7, c_8, c_9, c_{10}, c_{11}, c_{12}, c_{13}\},$$

while the unmatched constraints are:

$$\mathcal{U} = \{c_4, c_6\}.$$

Each of the unmatched constraints give a parity equation. In this way, the detection equations are derived by back tracing the matching of the unknown variables involves in the unmatched constraints until only known variables are part of the expression. The resulting parity equations are:

$$c_4(\omega, \nu, \omega_l) = 0 \tag{24}$$
$$c_6(x, y, \theta, d) = 0 \tag{25}$$

and back tracing unknown variables to known variables results:

$$c_4[y_{1,m}, c_5(y_{1,m}, y_{3,m}), y_{2,m}] = 0 \tag{26}$$

$$\begin{aligned} c_6[&c_7(c_1(c_9(c_3(y_{1,m})), c_5(y_{1,m}, y_{3,m}))), \\ &c_8(c_2(c_9(c_3(y_{1,m})), c_5(y_{1,m}, y_{3,m}))), \\ &c_9(c_3(y_{1,m})), y_{4,m}] = 0 \end{aligned} \tag{27}$$

This gives the following residuals:

$$r_\alpha = f_\alpha(y_{1,m}, y_{2,m}, y_{3,m}) \tag{28}$$

$$r_\beta = f_\beta(y_{1,m}, y_{3,m}, y_{4,m}) \tag{29}$$

4.2 Change detection algorithms: the decision module

The role of the decision module is to determine whether the residuals differ significantly from zero and, from pattern of zero and non-zero residuals, to decide which are the most likely fault effects, and in turn, which component/s could be the origin of a fault. Residual evaluation consists to detect a change in the mean of a normally distributed random sequence, which can be achieved by sequential change detection algorithms like the cumulative sum (CUSUM) algorithm (Basseville and Nikiforov, 1993). This algorithm is chosen to design the decision module of the fault detection system of the powered wheelchair.

5. EXPERIMENTAL RESULTS

The simulation results has confirmed the developed analysis. The same results are also obtained by experimental tests performed on the TGR module base where the implementation of designed fault system has been performed on the PC used for the navigation module.

The designed Sensor Fault Detection System is able to detect a single fault on the considered sensor equipment. Moreover, faults on laser scanner and left encoder can be isolated. The integration of this system with the navigation module introduces new capabilities for localising the mobile base when a single sensor fault is occurred. Therefore the designed SFDS increases the navigation reliability of the smart wheelchair. The SFDS has been integrated in the preexisting different levels of autonomy of the navigation module. For example, in the first level of autonomy, where a strong interaction with the user is required, the SFDS can be used for showing to the user the presence of a sensor fault. In this case, the system can request the interaction of the user who can command to ignore the fault or to stop the vehicle. In the other levels of autonomy, the SFDS can be used for detecting and isolating of the possible sensor fault in a complete automatic way. In this modality, if a sensor fault is detected but it can not be isolated, the SFDS stops immediately the vehicle. The faults signatures are resumed in the Table 2. The considered sensor equipment does not guarantee the necessary redundancy for isolating of all sensor faults. In any way, the sensor system is able to detect all sensor faults. Adding new sensors is possible to improve the performances of the proposed SFDS. This aspect is under investigation for further research activities. A significant experimental activity is under developing to analyze the reliability of the developed system for different environment conditions and mobile tasks.

Table 2. Effects of the faults on the residuals.

$\nearrow$	f_{gyro}	$f_{enc,l}$	$f_{enc,r}$	f_{laser}
r_α	$\times$	$\times$	$\times$	0
r_β	$\times$	0	$\times$	$\times$

6. CONCLUDING REMARKS

This paper shows how the proper development of a model-based Sensor Fault Detection System can improve the reliability and the safety of smart wheelchairs. In fact, the SFDS permits to prevent simples navigation sensor faults and hence to reduce the risk of safety hazards.

The design of the SFDS was based on the structural analysis which, using graph theory, permits to determine which redundancy exists in the sensory system and thus shows the possibility to detect and handle the navigation sensor faults.

Satisfactory simulation results has confirmed the developed analysis and an improved experimental architecture is under developing for further research activities.

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