A Virtual Fuzzy Actuator for the Fault-tolerant Control of a Rescue Vehicle

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***Abstract*—This paper intends to present a novel and promising application field for fuzzy logic: the realization of fuzzy virtual actuators. In the field of control and diagnosis, virtual sensors are successfully applied since several years. This kind of sensor applies a mathematical model and different sources of information, for instance the state of actuators or information from already existing sensors, in order to generate virtual measurements. Current research activities aim at complementing the concept of virtual sensors with the concept of virtual actuators. Virtual actuators are parts of a fault-tolerant control strategy and aim to accommodate faults and to achieve a safe operation of a faulty plant. So far, only few authors report the application of fuzzy logic to the concept of virtual actuators and this application is limited on a representation of the non-linear system with the Takagi-Sugeno fuzzy model. In the focus of this paper is a novel fuzzy virtual actuator which applies fuzzy rules in order to include experts knowledge. The application example is a rescue vehicle. The application of fuzzy logic rules allows to integrate experts knowledge into the decision making of the virtual actuator in the control system of the vehicle. It enables the accommodation of several possible faults, such as a slippery surface under one of the chains of the rescue vehicle.**

***Index Terms*—Model Predictive Control, Fault-Tolerance, Virtual Sensor**

I. Introduction

In recent years, so-called rescue vehicles were developed for the autonomous operation in insecure areas such as collapsed buildings. These vehicles are a special kind of Automated Guided Vehicles (AGV) with high requirements concerning safe operation and robustness. AGVs dispose of their own intelligence for determining their position, their state of motion and certain environment conditions. It is important to note that these environment conditions can be varied, such as the position of obstacles and the floor friction conditions. For the safe and efficient operation of AGVs, they have to sense their environment, they need to be capable of planning their future operations and they are required to be able to act accordingly to this plan [1]. In the field of general robotics, fuzzy logic control was employed because of its rather simple control structure as well as its easy and cost-effective design [2]. In recent years, many researchers have successfully applied fuzzy logic to the control of autonomous vehicles [3], [4]. Significant improvements were possible, because fuzzy control is able to cope with imprecise information. On a very general level, conventional fuzzy control and adaptive fuzzy control can be distinguished. In the field of conventional fuzzy control, Mamdani fuzzy control [5], [6] and Takagi-Sugeno-Kang fuzzy control [7] are well-known, whereas adaptive fuzzy control can be realised as self-tuning fuzzy control or direct adaptive control. It is important to note that hybrid approaches are also possible and intensively researched which combine fuzzy logic with other algorithms such as the well-known proportional–integral–derivative (PID) control, the sliding mode control (SMC) [8], neural networks [9], genetic algorithms [10], artificial bee colony optimization [11] and particle swarm optimization [12]. In the field of fault-tolerant control and especially in the field of fault detection and identification (FDI), fuzzy logic was used for realising virtual sensors. Virtual sensors have received large attention, because the increasing complexity of technical systems leads to an increasing demand for elaborate control and diagnosis systems for a safe and efficient operation [13]. These systems require sensory information, but the possibility to add additional sensors is often limited due to financial, space and weight constraints. The application of virtual sensors is a promising approach to address these issues. This kind of sensor generates virtual measurements by combining sources of information already present in a system (e.g. actuator states or sensors originally applied to provide other measurements) and mathematical models of the system. Numerous research activities aim to develop and implement virtual sensors, most of them in connection with Fault-Tolerant Control (FTC) and Fault Diagnosis and Identification (FDI) [13]–[15]. In general, three main kinds of virtual sensors may be distinguished:

- observer-based approaches [16], [17] (employing e.g. quadratic boundedness [18]); in some cases based on fuzzy logic [19], [20],
- filter-based approaches (employing e.g. Kalman filters) [21], [22] and
- parameter identification-based approaches [23].

Current research complements the concept of virtual sensors with the concept of virtual actuators; this concept is discussed in detail in the next section.

II. Virtual actuators

The concept of a virtual actuator was firstly proposed by Blanke et al. in the 2003 edition of their book [24]. These authors use the notion "virtual actuator" for the reconfiguration block in a control reconfiguration scheme (see Figure 1).

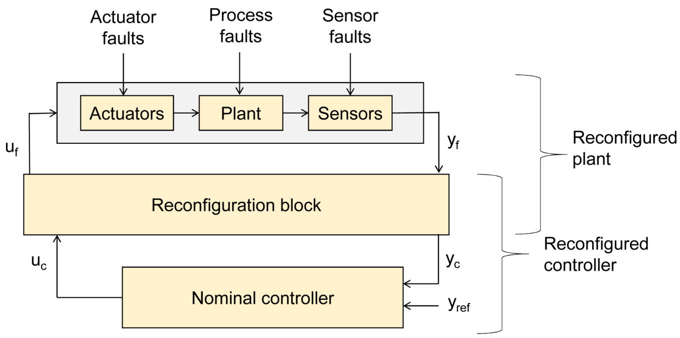

Fig. 1. Principle of control reconfiguration (compare [25]).

In scientific literature, several implementations of this concept are reported. Successful applications were a two-degree of freedom helicopter [26] and the lateral control of an aircraft (in form of a bank of actuators [27]). Further works investigate the application to LPV systems with saturating actuators and FDI delays [28]–[30]. Under investigation are also adaptive virtual actuators for the fault-tolerant control of linear systems [31], virtual actuators for the fault-tolerant control of discrete-time descriptor systems [32] and an actuator fault-tolerant control based on probabilistic ultimate bounds [33]. First research groups are reporting the realization of fuzzy virtual actuators [34]–[36], but the central focus is on the representation of non-linear systems based on the takagi-sugeno fuzzy model (compare [29]) and not on the application of fuzzy rules for including experts knowledge in the accommodation of faults.

A central prerequisite for the successful implementation of any virtual actuator is the capability of the plant to accommodate the present faults. It is only possible to accommodate a fault, if the actuators are able (e.g. strong enough and fast enough) to realize a safe and satisfactory state of the plant. Research intending to combine fault-tolerant design and fault-tolerant control [37] identified the methods over-actuation (compare [38], [39]) and actuator overlap as promising possibilities for holistic fault accommodation. Essentially, over-actuation means that more actuators are present than needed for the nominal operation [38], or alternatively that the present actuators are more powerful than needed for the nominal operation. Actuator overlap describes the design characteristic that two or more actuators have at least partly the same region of operation and can mutually compensate deficits, which are caused by faults, to some extend. A conscious integration of these characteristics in the system design may contribute to an increase of the fault-tolerance.

Taking the aspects listed above into consideration, it is proposed to expand the definition of virtual actuators as follows:

Definition 1
A virtual actuator consists of an appropriate means for control reconfiguration in a system which is able to detect and identify faults and to accommodate these faults through a conscious design of the sensor and actuator structure.

Based on this definition, a holistic implementation of a virtual actuator is elucidated in the following sections. A major part in this implementation is the integration of experts knowledge based on rules formulated in fuzzy logic.

III. Application Example

In recent years, mobile robots for rescue operations have found increasing attention (e.g. Kayisli et al. 2017 [40], Maruyama and Ito 2010 [41]). As a support in efforts to detect, to communicate with, to supply, and to save victims who are trapped for instance in the rubble of a collapsed building, relatively small rescue robots could enter the ruins before the site is secured. The requirements such robots have to fulfil are numerous and diverse. A large team of researchers and students was able to develop a mobile robot platform, shown in Figure 2, which is suited to meet the most important expectations of rescue organisations.

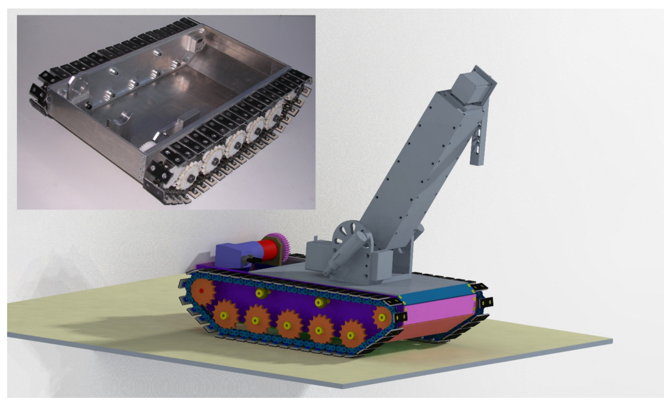

Fig. 2. Rescue vehicle.

In Figure 2 the realized chassis is visible in the upper left. The first development steps were described in [42].

IV. Mathematical model of the Rescue vehicle

The mathematical model for the control and diagnosis of the rescue vehicle is explained in this section; the respective notation is given in Table I.

The essential parameters of the rescue vehicle are given in Table II.

The essential kinematic and kinetic parameters are explained in Figure 3.

By means of analysing the forces acting on the rescue vehicle, it can be found that the force leading to motion in longitudinal direction can be found using the subsequent equation:

$$F_{y_c} = F_{y,1} + F_{y,2}. \quad (1)$$

TABLE I
NOTATION

COG	center of gravity
$i = 1, 2$	number of drive chains (left/right)
$m = x, y, z$	directions
a	distance between chain center point and COG
α	vehicle angle
$\dot{\alpha}$	vehicle angular velocity (yaw rate)
$\ddot{\alpha}$	vehicle angular acceleration
x_w, y_w	position of the vehicle in the world coordinate system
x_c, y_c	position of the vehicle in the center coordinate system
$\dot{x_c}$	lateral velocity of the vehicle
$\dot{y_c}$	longitudinal velocity of the vehicle
$\ddot{x_c}$	lateral acceleration of the vehicle
$\ddot{y_c}$	longitudinal acceleration of the vehicle
m	mass
β_j	angle of the i-th chain wheel
$\dot{\beta_i}$	angular velocity of the i-th chain wheel
$\ddot{\beta_i}$	angular acceleration of the i-th chain wheel
F_{x_c}	sum of forces causing lateral motion
F_{y_c}	sum of forces causing longitudinal motion
$F_{y,i}$	longitudinal force on the i-th chain
$F_{x,i}$	total lateral force on the i-th chain
T	total torque acting on both chain wheels
p_j	torque distribution coefficient
κ	coefficient summarizing additional inertia in the drive-train
μ_r	rolling friction coefficient
I_c	chain moment of inertia
I_z	vehicle moment of inertia around z-axis
R_e	chain wheel effective radius

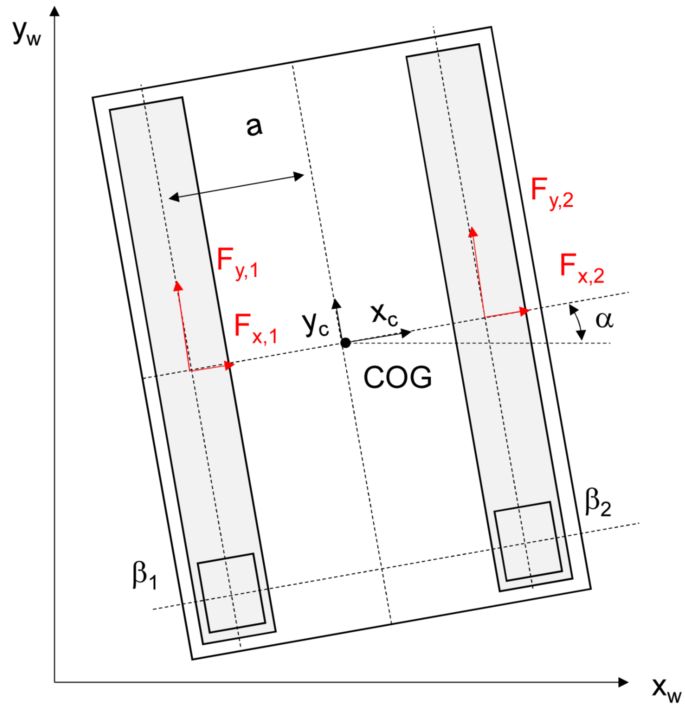

Fig. 3. Essential kinematic and kinetic parameters.

TABLE II
ESSENTIAL PARAMETERS

Variable	Unit	Value
m	kg	26.5
R_e	m	0.018
a	m	0.126
κ		1.2
μ_r		0.1

This analysis can also lead to an equation concerning the lateral forces:

$$F_{x_c} = F_{x,1} + F_{x,2}. \quad (2)$$

An investigation of the dynamic behaviour can lead to the subsequent formulations:

$$\ddot{y_c} \cdot m = F_{y_c}, \quad (3)$$

$$\ddot{x_c} \cdot m = F_{x_c}. \quad (4)$$

Using the longitudinal wheel forces, the wheel angular acceleration can be found using the following equation:

$$I_c \ddot{\beta_i} = p_i T - F_{y,i} R_e. \quad (5)$$

In the precedent equation, the torque distribution coefficients p_j are assumed to be known. Based on this, also the required torque for each motor driving one chain can be determined:

$$T_i = R_e \cdot p_i \cdot (\kappa \cdot m \cdot \ddot{y_c} + m \cdot g \cdot \mu_r) \quad for \quad i = 1, 2. \quad (6)$$

Furthermore, it is also possible to analyse the yaw rate dynamics using the following equation:

$$I_z \cdot \ddot{\alpha} = -a \cdot F_{y,1} + a \cdot F_{y,2}. \quad (7)$$

In the given case, it is admissible to assume that the measurement vector is available

$$y = [\dot{\alpha}, \dot{\beta_1}, \dot{\beta_2}]^T. \quad (8)$$

The analogous formulation of the state vector is:

$$x = [\dot{\alpha}, \dot{\beta_1}, \dot{\beta_2}]^T. \quad (9)$$

The elaborations listed above allow the development of a state space model that can be employed for the model predictive control of the movement of the rescue vehicle. Additionally, it enables fault diagnosis and fault-tolerant control based on the concept of a virtual actuator (compare section I). Through this, certain faults (reduced friction, reduced torque) can be detected and accommodated, as it will be demonstrated in the later parts of this paper. The state space model can be formulated as follows:

$$\dot{\boldsymbol{x}} = \boldsymbol{E}\boldsymbol{d}. \quad (10)$$

In this equation $\boldsymbol{x}$ denotes the state and $\boldsymbol{d}$ denotes the unknown input.

The unknown input that will be estimated by the virtual sensor is:

$$\boldsymbol{d} = [F_{y,1}, F_{y,2}, T]^T. \quad (11)$$

The system matrix in this state space model is:

$$E = \begin{bmatrix} -\frac{a}{I_z} & \frac{a}{I_z} & 0 \\ -\frac{R_e}{I_c} & 0 & \frac{p_1}{I_c} \\ 0 & -\frac{R_e}{I_c} & \frac{p_2}{I_c} \end{bmatrix} \tag{12}$$

This system can also be discretized using the Euler methods:

$$\boldsymbol{x}_{k+1} = \boldsymbol{x}_k + \boldsymbol{E}_k \boldsymbol{d}_k + \boldsymbol{W} \boldsymbol{w}_k. \tag{13}$$

with

$$\boldsymbol{E}_k = T_s \cdot \boldsymbol{E}, \tag{14}$$

where $\boldsymbol{w}_k$ stands for an exogenous disturbance vector (which includes the discretization error) with a known distribution matrix $\boldsymbol{W}$.

V. Fault detection and identification with a virtual sensor

The first phase in the application of a virtual actuator is the detection of faults. It is important to note that the system described in equation 13 has an unknown input d_k, which needs to be estimated for enabling fault detection and identification. In a prior publication, an adaptive estimator was proposed for a similar task [43]. This estimator is capable of estimating the unknown input d_k without relying on an estimation of the state of the system state x_k. For the given vehicle, the measurement can be described with the equation:

$$\boldsymbol{y}_k = \boldsymbol{C}_k \boldsymbol{x}_k + \boldsymbol{V} \boldsymbol{v}_k. \tag{15}$$

In this equation, $\boldsymbol{v}_k$ stands for the measurement noise and $\boldsymbol{V}$ for its known distribution matrix. It is possible to employ an unknown input estimator resembling the one proposed by Gillijns and De Moor [44]. The basis can be formulated for the given system in the subsequent form:

$$\hat{d}_{k-1} = \boldsymbol{M}_k (\boldsymbol{y}_k - \boldsymbol{C}_k \hat{x}_{k-1|k-1}). \tag{16}$$

In this equation, $\hat{x}_{k-1|k-1}$ is an estimate of $\boldsymbol{x}_{k-1}$. The innovation $\tilde{y}_k$ may be defined by

$$\tilde{y}_k \triangleq \boldsymbol{y}_k - \boldsymbol{C}_k \hat{x}_{k-1|k-1}. \tag{17}$$

In this estimation process, the unknown input $\hat{d}_{k-1}$ is estimated from the measurement $\boldsymbol{y}_k$ using the matrix $\boldsymbol{M}_k$. In order to be able to evaluate the estimation process a simulation was generated, which consists of a driving maneuver with a continuously increasing acceleration. A result of the estimation of the unknown input for the two longitudinal chain forces $F_{y,1}$ and $F_{y,1}$ as well as the total torque T is shown in Figure 4.

It is important to note that in Figure 4 the unit of the forces is Newton, whereas the unit of the torque is Newtonmeters. This fact leads to different sizing. Based on the estimation described above, three residual signals may be achieved, for example a residual signal for the total torque acting on both chains:

$$z_{T,k} = T_k - \hat{T}_k. \tag{18}$$

The other two signals concern the longitudinal forces on both chains:

$$z_{y,i,k} = F_{y,i,k} - \hat{F}_{y,i,k}. \tag{19}$$

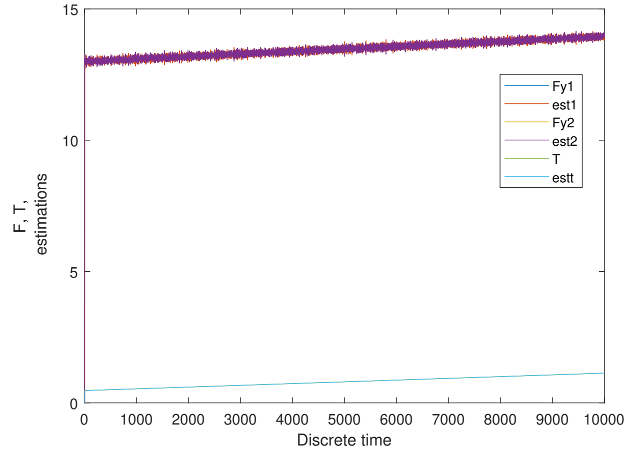

Fig. 4. Sample estimation result for two longitudinal forces and the total torque

VI. Design of a fuzzy virtual actuator

A fuzzy virtual actuator is a part of a fault-tolerant control system which allows a control reconfiguration in a system capable of detecting and identifying faults and capable of accommodating these faults because of a consciously designed sensor and actuator structure. The central characteristics of the fuzzy virtual actuator are described in this section. The input information for this fuzzy virtual actuator are the residuals generated by the virtual sensor (compare section V). The actuator is able to create a correction factor which may be applied to the sensor readings in order to enable the original controller to control the rescue vehicle. For the residual z_i, membership functions μ_{z_i} are derived that enable an initial evaluation of the individual residuals. For the objective of residual evaluation, trapezoidal membership functions were proposed in earlier research, because they are capable to describe the residuals in a simple and effective manner [43]. The width of the membership functions may be found by means of analysing the maximum and minimum values of the residuals; this means that these values can be determined experimentally. In order to accommodate process noises, disturbances and mismatches between analytical models and the plant, the core is a small interval around zero; its size may be found employing experimental data [45]. In advance of the development of the fuzzy virtual actuator, an in-depth analysis with design and control experts of the rescue vehicle was carried out. This analysis resulted in the insight that the combination of several residuals is beneficial for fault isolation. For example, in the case that the drive chains of the rescue vehicle would be on slippery ground, this fact will firstly be apparent in the residual for the longitudinal forces of the drive chains. However, also in the residual for the torque of the whole rescue vehicle this influence will be present. This fact allows to distinguish this fault from a sensor fault in the drive motors of the respective drive chain. Consequently, it can be concluded that the integrated evaluation of more then one residual can result in a higher certainty of the decisions, whether a certain fault is present. This decision allows the application of a correction factor to the velocity measurement of the respective drive chain. This measurement will not reflect the real vehicle speed, as a consequence of the slippery surface. The resulting layout of the fuzzy virtual actuator proposed in this section is shown in Figure 5.

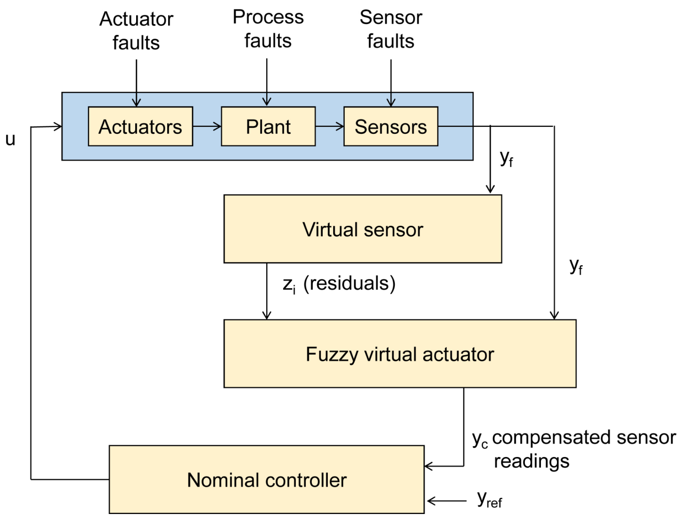

Fig. 5. Layout of the proposed fuzzy actuator

For the rescue vehicle, the knowledge of the experts concerning a given fault (slippery surface under the drive chains) was captured with three membership functions for each of the residuals z_i that serve as input of the fuzzy system. The first input membership function μ_{i1} was composed in the subsequent form:

$$\mu_{i1} = \begin{cases} 1, & z_i < c_{i1} \\ \frac{d_{i1}-z_i}{d_{i1}-c_{i1}}, & c_{i1} \leq z_i \leq d_{i1} \\ 0, & z_i > d_{i1}, \end{cases} \tag{20}$$

where c_{i1} and d_{i1} denote parameters that are determined based on the knowledge of experts or on experimental data (all trapezoidal membership functions are defined by a lower limit a, an upper limit d, a lower support limit b, and an upper support limit c, where $a < b < c < d$). This membership is intended to characterise the situation that the respective residual indicates a fault and that the value of the residual is negative, which, in this situation, indicates that the observed longitudinal force is smaller than the force analytically expected. The next membership function μ_{i2} is intended to indicate the situation that the respective residual is close to zero, consequently not indicating a fault. This membership function was composed in the subsequent form:

$$\mu_{i2} = \begin{cases} 0, & (z_i < a_{i2}) \quad or \quad (z_i > d_{i2}) \\ \frac{z_i-a_{i2}}{b_{i2}-a_{i2}}, & a_{i2} \leq z_i \leq b_{i2} \\ 1, & b_{i2} < z_i < c_{i2} \\ \frac{d_{i2}-z_i}{d_{i2}-c_{i2}}, & c_{i2} \leq z_i \leq d_{i2}, \end{cases} \tag{21}$$

where a_{i2}, b_{i2}, c_{i2} and d_{i2} are also parameters that are determined based on the knowledge of experts or on experimental data. The third membership function μ_{i3} can be composed in the subsequent form:

$$\mu_{i3} = \begin{cases} 0, & z_{i,j} < a_{i3} \\ \frac{z_{i,j}-a_{i3}}{b_{i3}-a_{i3}}, & a_{i3} \leq z_{i,j} \leq b_{i3} \\ 1, & z_{i,j} > b_{i3}, \end{cases} \tag{22}$$

where a_{i3} and b_{i3} are also parameters that are determined based on the knowledge of experts or on experimental data. This membership function is intended to characterise the situation that the respective residual indicates a fault and that the value of the residual is positive, which, in this situation, indicates that the observed longitudinal force is larger than the force analytically expected. However, this situation would be impossible in the case of a slippery surface. The presence of a positive value of the residual may only be caused by another fault.

Analogously, three membership functions are defined for the output variable which is intended to from the correction factor $\Delta\beta_{12}$. The first one μ_{o1} was composed in the subsequent form:

$$\mu_{o1} = \begin{cases} 1, & afo < c_{o1} \\ \frac{d_{o1}-afo}{d_{o1}-c_{o1}}, & c_{o1} \leq z_{i,j} \leq d_{o1} \\ 0, & afo > d_{o1}, \end{cases} \tag{23}$$

where afo denotes the aggregated fuzzy output and c_{o1} and d_{o1} are parameters that are determined based on the knowledge of experts or on experimental data. A value in this range will indicate the situation that another fault (e.g. a sensor fault) is present. The second output membership function μ_{o2} was composed in the subsequent form:

$$\mu_{o2} = \begin{cases} 0, & afo < a_{o2}) \quad or \quad afo > d_{o2}) \\ \frac{afo-a_{o2}}{b_{o2}-a_{o2}}, & a_{o2} \leq afo \leq b_{o2} \\ 1, & b_{o2} < afo < c_{o2} \\ \frac{d_{o2}-afo}{d_{o2}-c_{o2}}, & c_{o2} \leq afo \leq d_{o2}, \end{cases} \tag{24}$$

where afo also denotes for the aggregated fuzzy output while a_{o2}, b_{o2}, c_{o2} and d_{o2} are parameters that are determined based on the knowledge of experts or on experimental data. In this situation the correction factor will be zero. The third output membership function μ_{o3} was composed in the subsequent form:

$$\mu_{o3} = \begin{cases} 0, & afo < a_{o3} \\ \frac{afo-a_{o3}}{b_{o3}-a_{o3}}, & a_{o3} \leq afo \leq b_{o3} \\ 1, & afo > b_{o3}, \end{cases} \tag{25}$$

where afo again denotes the aggregated fuzzy output, while a_{o3} and b_{o3} are parameters that are determined based on the knowledge of experts or on experimental data. In the given case in the specific situation it was possible to use these functions to directly determine a correction factor. It should be noted that in many cases additional calculations can be necessary for deriving a correction factor $\Delta\omega$ using the direct output of the fuzzy inference system.

Figure 6 contains the structure of the fuzzy inference system, gives an example for the membership functions of one residual (input) and shows the membership functions for the correction factor (output).

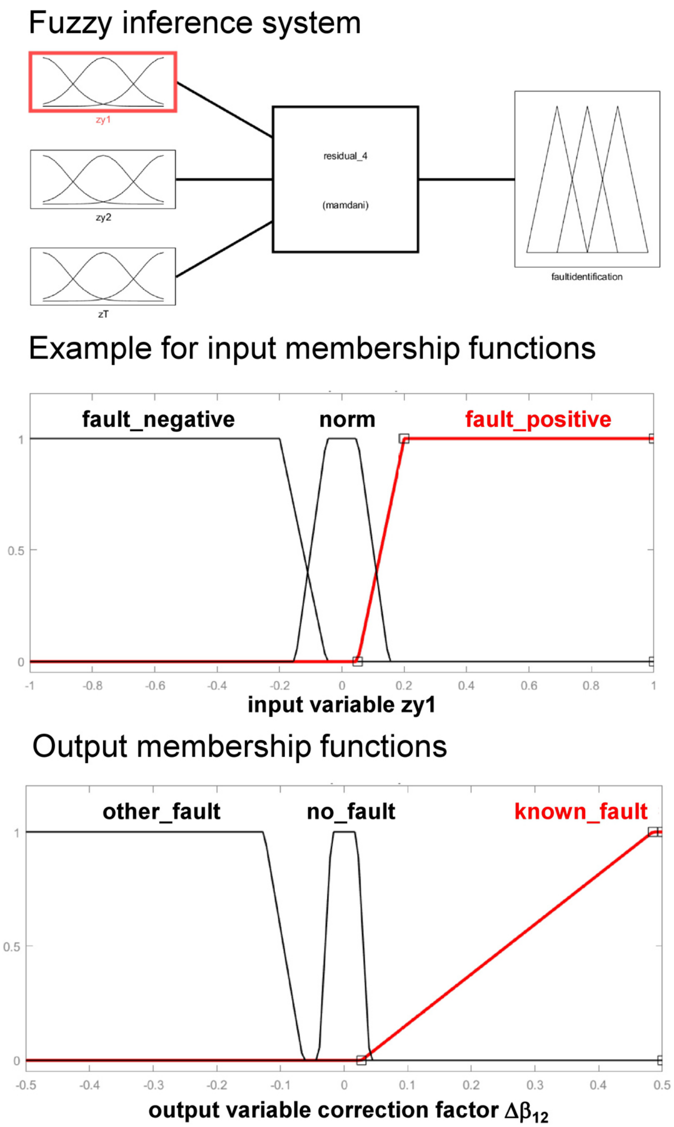

Fig. 6. Structure of the fuzzy inference system, membership functions for the evaluation of one residual and correction factor generation

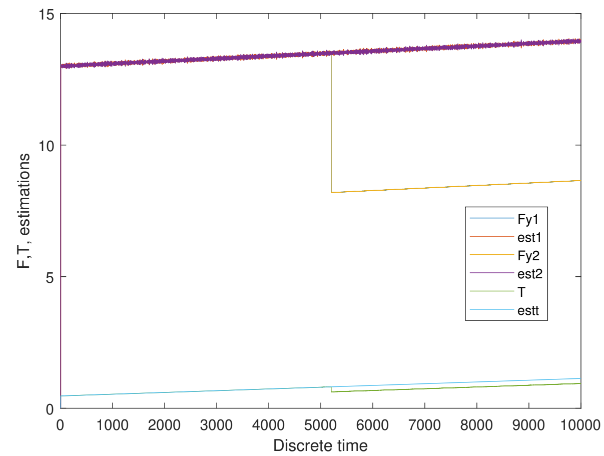

Fig. 7. Scenario with fault at k = 5000

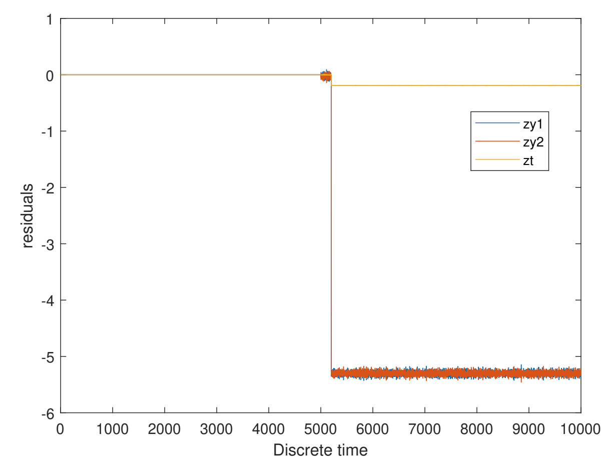

Fig. 8. Resiudals generated by the virtual sensor

All membership functions, parameters and rules of the fuzzy inference system were defined based on the knowledge of experts. The fuzzy inference system incorporates information from more than one residual for a well-founded fault identification and the sizing of correction factors for certain measurements.

VII. Evaluation

The evaluation concentrated on a situation which may be present in a collapsed building due to broken pipes or fire-fighting foam. The assumed fault consists of a reduced friction on the drive chains due to a slippery surface. A corresponding simulated set of forces and total torque is shown in Figure 7.

The resulting set of residuals originating from the virtual sensor described in Section V is presented in Figure 8.

The residuals shown in Figure 8 were used as an input for the realized fuzzy inference system which disposes of three individual membership functions for each residual. The rules, which are based on the knowledge of experts, combine the information of all residuals for allowing a decision whether a certain fault is occurring. As a consequence of the special nature of fuzzy logic, it is additionally possible to asses the size of the fault and to determine a correction factor for one of the measurements (compare Figure 9).

In Figure 9 the fact is clearly visible that very close to the appearance of the fault, the correction factor is set to a sensible numerical value. This factor may allow that an unaltered controller is able to control the rescue vehicle.

VIII. Conclusions and Outlook

The main contribution of this paper is the proposal of a fuzzy virtual actuator which incorporates expert's knowledge into the identification of faults and the creation of correction factors for accommodating these faults. Up to now, several kinds of virtual actuators were proposed in literature, but the only class of fuzzy virtual actuators mentioned was focusing

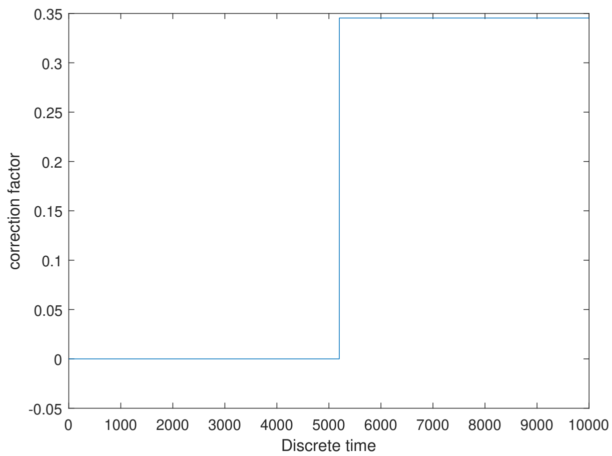

Fig. 9. Correction factor β_{12} generated by the virtual actuator

on the representation of a nonlinear system by means of the Takagi-Sugeno fuzzy model. The novel fuzzy virtual actuator applies fuzzy rules which represent the expert's knowledge and/or experimental results. The proposed concept disposes of the advantageous quality to sensibly combine the information from more than one residual for increasing the decision certainty in fault detection and isolation. Another advantageous quality is the capability of generating numerical values for correction factors. The fuzzy inference system is combined with a virtual sensor based on unknown input estimation; the performance could be demonstrated on the example of a rescue vehicle. A connected investigation is concerning the fault-tolerant design of balanced two-wheel scooters; the results concerning a fuzzy decision engine indicate the applicability of a similar concept and highlight the fact that it is a key factor for increasing the fault-tolerance to interconnect design characteristics and diagnosis algorithms [46]. It is probable that the fault-tolerant control strategy could be applied to other types of AGVs (e.g. AGVs with tricycle kinematics); in fact, this is a promising field for scientific activity. The results of these activities may lead to additional applications in industry and the daily life of human customers. Up to now, the stability was not formally proven and no detailed comparison with other forms of virtual actuators (PID or Fuzzy Takagi-Sugeno) was carried out; this will be topic of further research work. Additional scientific activity is also desirable for investigating the influence of disturbances on this control scheme and how they can be dealt with. Further research work is also planned that will concentrate on the generation of a systematic formulation scheme for membership functions and rules.

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