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Published by
Impressum

Publisher Herausgeber	Der Rektor der Technischen Universität Ilmenau Univ.-Prof. Dr. rer. nat. habil. Dr. h. c. Prof. h. c. Peter Scharff
Editor Redaktion	Referat Marketing und Studentische Angelegenheiten Andrea Schneider Fakultät für Maschinenbau Univ.-Prof. Dr.-Ing. habil. Peter Kurz, Univ.-Prof. Dr.-Ing. habil. Rainer Grünwald, Univ.-Prof. Dr.-Ing. habil. Prof. h. c. Dr. h. c. mult. Gerd Jäger, Dr.-Ing Beate Schlütter, Dipl.-Ing. Silke Stauche
Editorial Deadline Redaktionsschluss	17. August 2008
Publishing House Verlag	Verlag ISLE, Betriebsstätte des ISLE e.V. Werner-von-Siemens-Str. 16, 98693 Ilmenau

CD-ROM-Version:

Implementation Realisierung	Technische Universität Ilmenau Christian Weigel, Helge Drumm
Production Herstellung	CDA Datenträger Albrechts GmbH, 98529 Suhl/Albrechts

ISBN: 978-3-938843-40-6 (CD-ROM-Version)

Online-Version:

Implementation Realisierung	Universitätsbibliothek Ilmenau ilmedia Postfach 10 05 65 98684 Ilmenau

Home / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=17534

53rd Internationales Wissenschaftliches Kolloquium
Technische Universität Ilmenau
08 – 12 September 2008

Safety mechatronics for industrial collision detection in human-machine interaction

Thema: Intelligent Mechanics in Robotics

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Keywords

Safety mechatronic, collision detection, human- machine interaction

Introduction

This paper describes safety methods for collision detection for human- machine interaction with industrial robots. For interaction it is a requirement, that the components must be safe, which means safe in electrical and mechanical design the functional safety. We present one solution for collision detection for endeffector tools. The theoretical model of collision detection, signal time based detection and multi-body safety control is discussed for implementation on the basic electrical safe microcontroller board. The behavior of new mechanical tests for the closed safety loop is discussed in the opposite of control-loops without sensor based failure detection. The conclusion gives an outlook about the experimental results and the possibility of free human-machine interaction without fences.

Theoretical model

Sensor based collision detection algorithm uses multi-body Newton-Euler equations of motion to solve the relation between signals from a force-moment sensor, accelerometer and three angular-rate velocity sensors.

The unbalance of the equation is then classified as external collision force $\vec{F}_{Collision}$ or collision moment $\vec{M}_{Collision}$.

If $\vec{F}_{Collision}$ or $\vec{M}_{Collision}$ exceeds the allowance preset the algorithm determine the collision is occurred. In figure 1, the mass represents the object which the robot holds, such as a machine tool. The mass is moveable in all possible directions of freedom so the reactive force is computed [6].

The equation of motion is examined as:

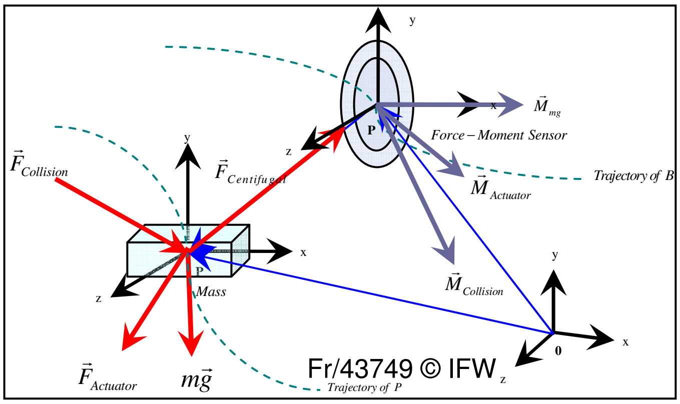

Figure 1: Analytical equations of a mass mounted on the robot endeffector as a multi-body system

$$\begin{aligned}&\vec{F}_{mess}-m\vec{a}_{mess}-m\dot{\vec{\omega}}\times\vec{r}_{BP}-m\vec{\omega}\times\left(\vec{\omega}\times\vec{r}_{BP}\right)-m\vec{g}=\vec{F}_{Collision}\\&\vec{M}_{mess}-\vec{r}_{BP}\times m\vec{a}_{mess}+J^{(B)}\cdot\dot{\vec{\omega}}+\vec{\omega}\times(\vec{J}^{(B)}\times\vec{\omega})-\vec{r}_{BP}\times m\vec{g}=\vec{M}_{Collision}\end{aligned}\tag{1}$$

Another safety feature is the model-based safety monitoring, which is established by system modeling and parameter identification of robot mechanism and its manipulators. Robot mechanism is definable using inverse kinematic. Together with modeling of robot manipulators, each non-linear three-phased permanent magnet synchronous motor (PSM) including Pulse-Width-Modulator (PWM) is done. For PSM, the model is developed under field-oriented coordinate which is straightforward for moment and rotational speed defining. PSM and PWM work as modules and can be extended or recomposed to suit a further application. Every model parameters, such as robot geometry, electrical properties of PSM and PWM are identified and finally give a complete robot model in figure 3. The model takes the trajectory of the real robot and computes every state variable in manipulators. This complete model is usable as a module for inverse kinematic and state observer or safety monitoring for each manipulator.

Figure 2 concludes this work with “on-line off-line robot control strategy with sensors-based collision detection and model-based safety monitoring”. The structure of control strategy is extended from conventional on-line off-line robot control, which compensates only the task handling accuracy. Two safety features are incorporated into the off-line robot control loop. The sensors-based collision detection is dedicated for protecting the object surrounding the robot, such as human from damage by the robot in case of collision. Whereas the model-based safety monitoring observe the internal state variables of each manipulators, this predicts a malfunction occurs to the robot during operation by examine the difference of electrical voltages and currents of both the model ones and real ones, thus the robot is self failure detectable and prevent the damage widen from itself to the surrounding.

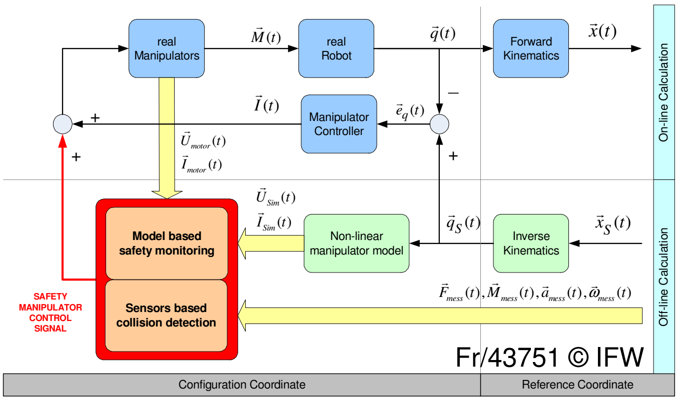

Figure 2: Complete dynamic structure model of industrial robot co-simulation with MSC.ADAMS

Additional safety features complete control strategy by utilizing well-known task handling capability of the conventional control and also another control procedure regarding safety [1], [2]. In case of robot end effector collides with nearby object or a malfunction in manipulators occurs, the control strategy introduced in this work should correctly detect and react by give a control signal to control each manipulators. This concludes and brings a step closer [3], [4], [5] to allow an industrial robot to perform at its maximum ability, while maintains a satisfactory level of safety.

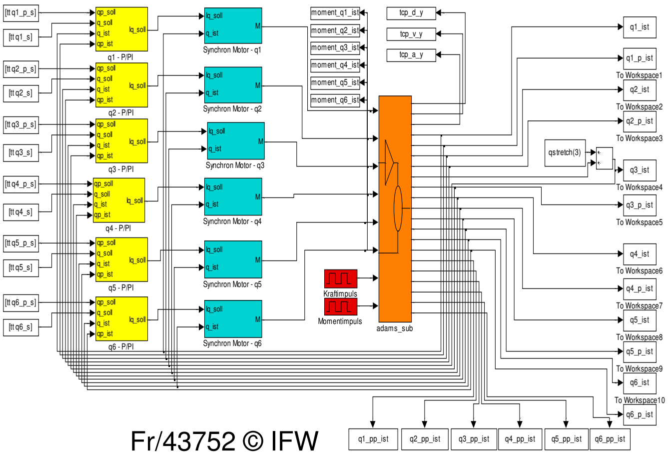

Figure 3: On-line off-line robot control strategy with sensors-based collision detection and model-based

Background of demand for mechanical parts tests in safety systems

Applications for human-machine interaction demand sensors to measure the force or acceleration. This mechanical system has the advantage, that they obtain the interaction between the process and a collision with a human body. But without any information of the mechanical stress and sensor measurement, it is not possible to say, that the sensor works correct. Therefore a mechanical test control loop is needed. Mechanical signals are possible to insert by a lot of actuators e.g. excenter, shaker, piezo actuator and so on. With this actuator it is possible to put defined mechanical stress into mechanical elements with a constant square based force behavior. The stresstime should be very low (in microseconds), that this mechanical test does not disturb the normal operation conditions of the mechanical parts. Figure 4 shows the possibility to test online mechanical parts of systems and to examine the transfer function of this mechanical part plus the sensor function. Then the whole safety chain is tested. Furthermore the mechanical tests use the elastic behaviour of the used part, that no abnormal condition could be appearing.

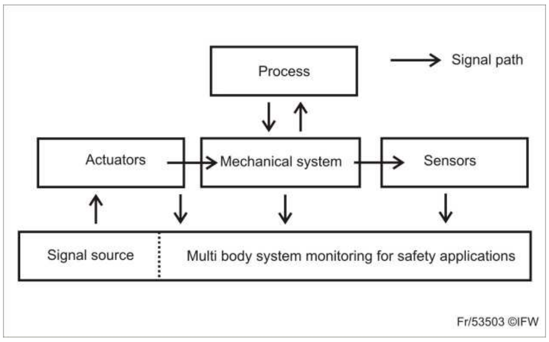

Figure 4: Safety test path for mechanical system components

To analyse and to create defined process parameters, which will be observed during the process, the correlation between sensor signals of the actuator and the sensor could be used. With this information, the frequency transmission thru mechanical multi- body parts could be computed. Thus, the cross correlation function is a good tool, to examine the relation between the transfer function. This is computed by equation (2) with the inverse of the Fourier transformation of the cross power spectrum.

$$R_{xy}(\tau)=\int_{-\infty}^{\infty} S_{XY}(f)\cdot e^{j2\pi f\tau}df \qquad (2)$$

If a correlation appears around 1, it is possible to examine the same signal behaviour in the original and the compare signal. With a monitoring system in the frequency range, it is possible to put a square impulse to the actuator, transfer thru the mechanical system, and read it back by the sensors. Therefore the result is information about the frequency hopping and amplitude of the transfer function.

With the analysing method of the correlation it is possible to understand the frequency transmission thru multi body systems like in this application, mechanical motor part, crank, screw and force moment sensor. It is also possible with this method, to use actuators like piezoelectric components for thin film actuation to initiate force and moment signals in mechanical parts.

Signal based collision detection for industrial robots with internal robot data

Signal monitoring is a method adapted for collision detection. However a robot model makes sense for the monitoring of the robot kinematics. Both methods can be used parallel and give a reaction signal as shown in figure 5. The major difference of both methods is the measurement of external sensor signals and internal signals of the robot control, which can be readout over the Profibus. A force- moment sensor and an acceleration sensor are mounted at the end-effector as external sensors. At first both procedures are tested offline with a sample process (trajectory) in Matlab. Later the procedures can be implemented on a safety micro processor for online verification.

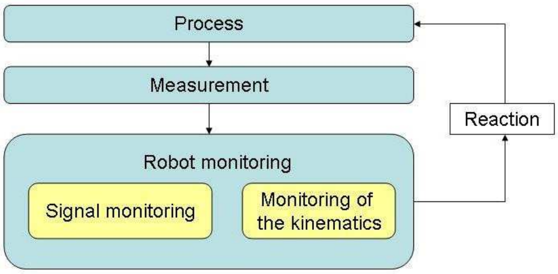

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Figure 5: Parallel monitoring of a robot

The method of the signal monitoring is divided in three phases: the learning phase, the monitoring phase and the adaptation phase. Time and statistical thresholds will be built in the learning phase. In the monitoring phase the measurement is checked that the values are inside of the upper und lower thresholds.

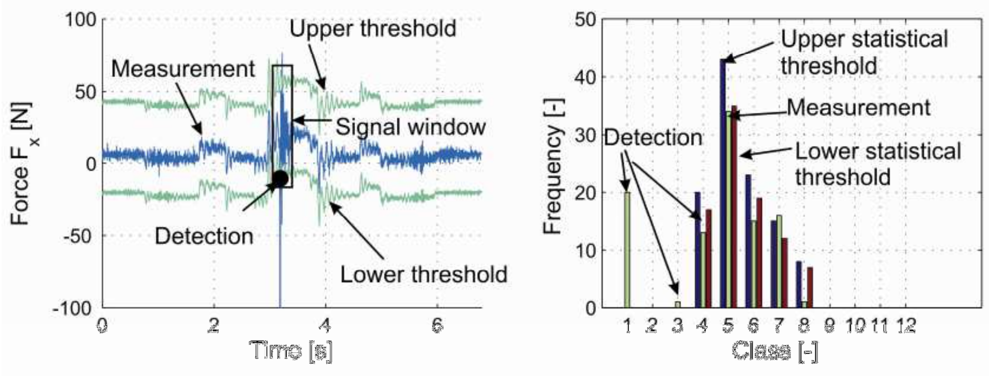

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Figure 6: Signal windowing, computing statistical thresholds and monitoring

Figure 6 shows the collision detection with thresholds in the time domain (left) and statistical thresholds (right). The thresholds in the time domain are built with eq. (3)

$$Y_{G,lower}(i) = Y(i) - w \cdot 5\sigma$$
$$Y_{G,upper}(i) = Y(i) + (2-w)5\sigma \qquad (3)$$

With

$$w = \frac{\max(Y(i)) - \mu}{\mu - \min(Y(i))} \qquad (4)$$

There is $Y_G(i)$ the built upper and lower threshold, $Y(i)$ the measured value, σ the standard deviation and μ the mean value of the process, w as a weighting factor.

A new approach for making method of the signal monitoring more robust is to build statistical thresholds through signal windowing. The time span of this signal window is defined by the developer and is addicted of the sample rate and the number of measured values. The example in figure 6 has a time span of 10ms with sample rate of 10Khz. Subsequent a window histogram is generated with the measured values in every window. The histogram gets a defined number of discrete classes with a set frequency. The lower und upper statistical thresholds are built with add und remove a defined frequency in every class (figure 6 right). The frequency of the measured values has to be inside of the statistical thresholds. In figure 6 a collision was detected after 9ms, because the measurement exceeds the statistical thresholds *and* in the time domain. If the measurement is error-free, because there is no collision in the process, both thresholds will be adapted in the adaptation phase. The adaptation of the thresholds in the time domain occurs with eq. (5)

$$Y_{G,upper}(i) = \overline{Y}(i) + w \cdot 5\overline{\sigma}_{new}$$
$$Y_{G,lower}(i) = \overline{Y}(i) - (2-w)5\overline{\sigma}_{new} \qquad (5)$$

with

$$\overline{\mu}_{neu} = \left(\overline{\mu}_{alt} \cdot (z-1) + \mu_{neu}\right)\frac{1}{z} \qquad (6)$$

$$\overline{\sigma}_{neu} = \left(\overline{\sigma}_{alt} \cdot (z-1) + \sigma_{neu}\right)\frac{1}{z} \qquad (7)$$

Similarly the statistical thresholds will be adapted. Overall the method of the signal monitoring with time and statistical could be suitable for collision detection.

To build a model of the kinematics is another method for monitoring a robot. This model is built in Matlab and gets internal signals of the robot control.

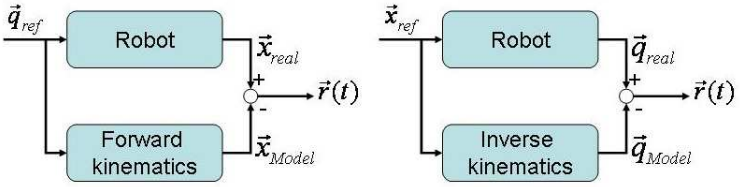

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Figure 7: Principals of monitoring the kinematics

Figure 7 shows the two principals of monitoring the robot kinematics. First the forward kinematics can be calculated from the reference link position as input values. Second the inverse kinematics can be calculated from the reference pose of the endeffector. The outputs can be compared with the position and pose of the real robot. If the residual is outside of a tolerance band, the robot will be stopped.

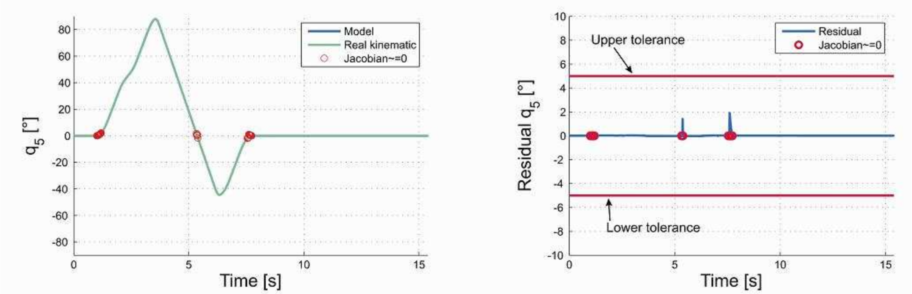

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Figure 8: Residual of a link position

Figure 8 (left) shows e.g. the time signal of the model and the real joint 5 when the robot moves. Model and real robot agree in together. Figure 8 (right) shows the residual of the joint position after calculating the inverse kinematics. Also there are marked some values. At these points the Jacobian trends against zero and the residuals get higher. But the residuals are small enough to be inside of a pre-defined tolerance band.

For the other links, similar results are achieved. So the method of monitoring the kinematics can be taken to detect variations between model and reality. This, as a result, provides two safety features; sensors based collision detection of the robot to its working environment and a model-based safety monitoring. Theses are extendable to be part of the robot control loop by mean of safety rather than just accuracy of task handling in conventional control strategy.

Electronic Componts for safety collision detection

Safety Microcontroller Board (SMB) is a device that is used to prevent risk in human and industrial robots cooperation. SMB consists of three parts; dual microcontroller, A/D Converter, and Fail Safe Logic (FSL). SMB is developed by using the structure known as "one out of two diagnoses (1oo2)". The Safety Integrity Level (SIL) of SMB is rated by Hardware Failure Tolerance (HFT) method, which indicates that all electronic components must be separated to several failure rates λ (Figure 10). Consequently, Diagnostic-Coverage (DC) and Safe Failure Fraction (SFF) values can be calculated by the equations provided below [7], [8], [9]. SIL value can be identified by comparison SFF value to the SIL classification table in the industry standard IEC 61508 (functional safety of electrical/electronic/programmable electronic safety-related) [13]. As a result, SIL of SMB is classified as SIL3. As tested by simulation of collision, SMB's operation is able to judge any situation and OSSD signal is send, whenever the collisions appear.

These SMB is in use for three different ways. The first is test the calculation of equation 1 during the movement of the robot. If a collision appears, the SMB send a signal directly to the robot controller to stop the robot. The second way is to use the internal robot signals e.g. motor current for an independent collision control. The third way is to calculate the kinematics and the robot dynamics as shown in figure 8. If any variant appear between the internal robot data and the external kinematic computed on the SMB, the robot will stop the production procedure.

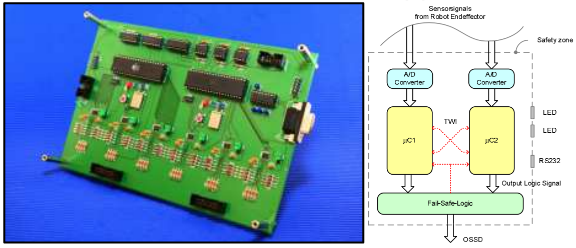

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Figure 9: Safety microcontroller board and structure of safety microcontroller board (SMB)

$$DC = \frac{\sum \lambda_{DD}}{\sum \lambda_D} \tag{8}$$

$$SFF = \frac{\sum \lambda_S + DC \cdot \sum \lambda_D}{\sum \lambda_S + \sum \lambda_D} \tag{9}$$

The structure of SMB is shown in figure 9. The components inside a dash box are identified as a safety zone, which must not be broken down when there is a failure from the outside. Twelve signals from three separated parts; a force- moment sensor, accelerometer, and an angular-velocity sensor of robot end effector, are converted to 8bits digital data and transferred to microcontroller by using Serial Peripheral Interface (SPI).

Each of the microcontroller receives the same data from A/D converter, in spite of the algorithms are different. Therefore a collision at robot end effector is guaranteed. Whenever the collision appears, both output logical signals from microcontrollers must be sent to FSL. Consequently, they are compared by logical gate in FSL section and will be converted to 24V level for OSSD signal which can stop the robot from collision [10].

According to the important role of FSL in termination of a collision, all electronic components in this section must be inspected. The inspection can be performed by using a test impulse signal; the red dash line in figure 9 is the inspection path. The test impulse signal is generated from any of the microcontrollers [11], [12]. If all elements in FSL still operate, the other microcontroller should get the same test impulse signal. It should be considered that the test impulse signal must be faster than the sensitivity of PLC. Otherwise, it will be recognized and disturb the PLC's program. As tested by simulation of collision, SMB's operation is able to judge any situation and OSSD signal is send, whenever the collisions with mechanical parts appear.

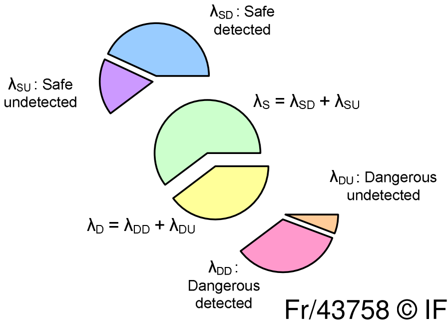

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Figure 10: Allocation of failure rates

Experimental results

As written down in chapter “tests for mechanical parts in safety systems”, it is necessary to use identification procedures to test the mechanical system with test impulses which are created by an actuator. Then the used sensor is able to replay this test signal and the correlation between the actuation signal and the sensor signal decides how the safety chain works. As an example, figure 11 shows the possibility to examine the correctness of the sensor system. One DC drive powers a shaft with a torque and the shaft begins to rotate with the rotating frequency. That eccentricity results a vibration which is transferred over the screw terminal to the force moment sensor. After an analysis of the sensor signals, the correlation is high between the acceleration inducted by the vibration and the important force signal. This shows figure 11 where, for example the second order vibration is printed isolated. Furthermore, an amplitude modulation is induced by the test signal. This could be shown by the sidebands in the frequency area.

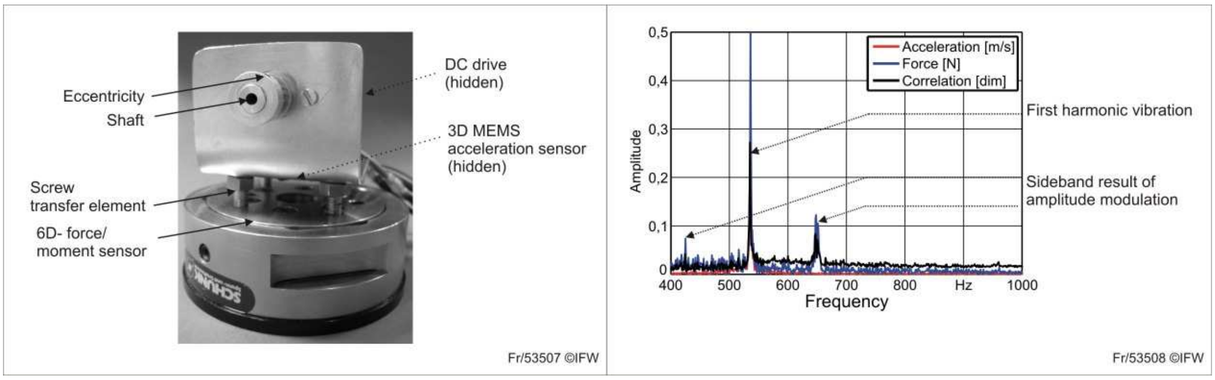

Figure 11: Mechanical tests thru stimulated actuator test frequencies, first harmonic vibration of one eccentricity; the correlation factor between the sensor force and induced acceleration.

As a result, with this method it is possible to test a lot of mechanical parts e.g. sensors by induced mechanical stress. Furthermore it is possible to decide, when a sensor failed and when this sensor have to create a warning message or the underlying safety management system initiate a stop of the movement of the robot controller.

Conclusion

Figure 12: Free human- robot cooperation

The aim of this research activities is enable an industrial robot cooperation and to be able to capable a handling of a massive high temperature metal forming process.

A new approach to identify collisions during work together with industrial robots is used. The theoretical background is described as collision detection with external force moment sensors. If it’s possible to use the internal robot data, it is possible to use the described signal processing algorithms with time based monitoring or with statistical monitoring of e.g. motor currents. For detection of variations and errors of the robot controller, a multi-body system controller was described. This controller recognizes unconditional behaviors and forces the robot controller to stop with a safety PLC. To implement this software, a safety microcontroller board was developed and approved. Therefore, a safety integrated level development was used. To fulfill the requirements of a full safety chain, the method of integration test signals in mechanical components is described, which closed the requirements of a full safety chain. Now it is possible, to solve the challenge of human- machine interaction without fences and to improve production with a free cooperation.

ACKNOWLEDGEMENT This research and development project is funded by the German Federal Ministry of Education and Research (BMBF) within the Framework Concept ”Research for Tomorrow's Production" (02PB2163) and managed by the Project Management Agency Forschungszentrum Karlsruhe, Production and Manufacturing Technologies Division (PTKA-PFT).

References

[1] Denkena, B.; Hesse, P.: Neue Sicherheitskonzepte als integraler Bestandteil moderner Automatisierungslösungen. In: Drive World, S. 14 – 17, 2004.
[2] Denkena, B.; Hesse, P.: Raus aus dem Käfig. Neue Sicherheitskonzepte ersparen lästige Schutzeinrichtungen. In: IndustrieService, S. 10 – 11, 2004.
[3], Denkena, B.; Behrends, B.; Hesse, P.; Friederichs, J.; Wedler, A. et al.: Adaptronische und sichere Schlüsselkomponenten für die Servicerobotik in der Produktion „koSePro". Berlin: Statustreffen, BMBF,11.2006
[4] Denkena, B.; Hesse, P.; Friederichs, J.; Wedler, A.: Adaptronische und sichere Schlüsselkomponenten im Anwendungsgebiet moderner Automation. Baden-Baden: VDI GMA Kongress, 03.2007
[5] Denkena, B.; Hesse, P.; Friederichs, J.; Wedler, A.: Schlüsselkomponenten für Roboter in der Produktion. Kaiserslautern, 08.2007
[6] DE 10 2006 055 849 A1: Verfahren zur sicherheitsgerichteten Abschaltung von Bewegungsvorgängen im Kollisionsfall. 2008
[7] DIN IEC 61508: Funktionale Sicherheit sicherheitsbezogenener elektrischer/elektronischer/programmierbarer Systeme, Norm-Entwurf, VDE 0803-1, 07.2006
[8] DIN EN ISO 10218: Industrieroboter – Sicherheitsanforderungen (ISO/DIS 10218/2004), 2005
[9] DIN EN ISO 13849-1: Sicherheit von Maschinen, Norm-Entwurf (ISO/DIS 13849-1:2004), 06.2004
[10] Hesse, P.; Schnebeck, T.; Habermann, S.: Sicherheit von Antriebssystemen - Der sichere Halt. In: Atp-Automatisierungstechnische Praxis, S. 34 – 36, 2004.
[11] Kiel, H. (Hrsg.): Antriebslösungen, Mechatronik für Produktion und Logistik, Lenze Drives Systems. Berlin: Springer, 2007
[12] Wedemeyer, T.: Sichere Antriebskonzepte, SPS-Magazin, Ausgabe 5, 2008
[13] Wratil, P.: Technology of safe Drives, IEEE-Publication, INDIN 2007, ISBN: 1-4244-0864-4, 2007

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