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THE DESIGN OF MOVEMENT OF THE ROBOT MODEL IN STRUCTURED ENVIRONMENT USING MSC ADAMS

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Keywords: computer simulation, manipulator, kinematic analysis, trajectory, matrix method
Abstract: In this work, the issue of kinematic analysis of the open kinematic chain of an industrial robot is discussed. The aim of the work lies in the kinematic analysis of the robot and the display of kinematic quantities in the work process. Transformation matrices of coordinate systems of individual members are determined for the solution by the matrix method. The direct method of kinematics using the MSC Adams View program is solved. The result is a graphical representation of the kinematic variables of the mechanical system of the end point of the effector and trajectory when moving in its working space.

1 Introduction

The issue of solutions of industrial robots is currently becoming more and more topical, because increasing the level of production and control after exhausting the known possibilities can be done only by automation and artificial intelligence, which will replace much of the necessary human participation in the production process. As in other fields, robotics is characterized by an effort to find general methods for solving entire sets of problems. An industrial robot is a device with multi-position motion units and its own drive and control with a flexible program for automatic operational and inter-operational manipulation of working machines or performing technological tasks. Industrial mobile robot is better solution, because smaller robot with locomotion function can be used instead of big fixed platform industrial robot. Industrial mobile robot can be used also for long distance handling with products in production process.

The paper shows the advantage of computer simulation, which allows you to create a virtual prototype of the device and modify it or create new variants without making the real device. It is possible to study the change in behavior of these different variants of the model. We can also simulate the proposed model in its work cycle. This will show possible collisions of its elements and evaluate various parameters of interest. The result is visualized in their program. It is possible to understand the operation of the model and subsequently verify its effectiveness. We can check the values of various parameters in the respective output views of the simulated model in real time.

2 Model of manipulator

The aim of the paper is the movement of a mobile robot in a structured environment. The robot consists of a handling arm mounted on a mobile chassis. We are interested in the trajectory of the effector endpoint. The generalized coordinates matrix method would be suitably used in the analytical solution of kinematics.

The configuration of the system with respect to the reference configuration is described by the generalized coordinates described q with q_i* (Figure 1). These indicate the motion (rotation or translation) in the individual axes. Configuration of the model with 5 degrees of freedom of movement is shown in Figure 1 [1-5].

The model consists of five members and a base marked 0. The arms of the robot are connected to each other by rotating kinematic pairs. The drives are in the appropriate kinematic pairs. The motion in kinematic pairs is described by generalized coordinates q.

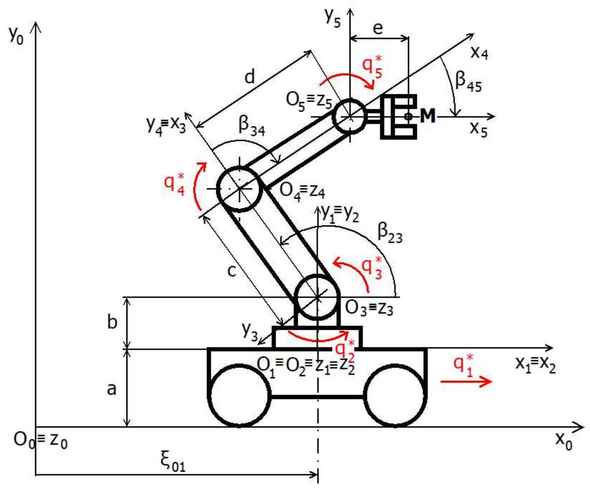

Figure 1 Model of the manipulator

The choice of the coordinate system is very important in order to be able to investigate the movement of the mechanism of the respective industrial robot in space. In this case, we will use a clockwise Cartesian coordinate system. In the matrix method we use translation matrices, which transfer the transformations of one coordinate system to another.

We consider the reference coordinate system $O_0(x_0, y_0, z_0)$ connected with base 0. For each member of the kinematic chain we define its local coordinate system. For nth member it is $O_n(x_n, y_n, z_n)$. The location of an individual member in the global coordinate system is then determined using the local coordinates systems of the other members. The coordinate system $O_1(x_1, y_1, z_1)$ was created by moving the coordinate system along the x_0 axis by ξ_{01} and along the y_0 axis by a. Other offsets of coordinate systems are apparent from Figure 1. The relation between the coordinates of the point M in the global and nth local coordinate systems can be expressed by using the transformation matrix notation [1-5] and takes the following form:

$$\bar{r}_{0M} = \boldsymbol{T}_{0n}\bar{r}_{nM} \tag{1}$$

Where $\bar{r}_{0M}$ – is the position vector of point M, $\bar{r}_{nM}$ – is the position vector of point M in the n-th local coordinate system.

The matrix $\boldsymbol{T}_{0n}$ in equation (1) then takes the form (2):

$$\boldsymbol{T}_{0n} = \boldsymbol{T}_{01}\boldsymbol{T}_{12}\ldots\boldsymbol{T}_{n-1,n} \tag{2}$$

It represents the transformation matrix of the resulting motion. It is given by the product of transformation matrices of elementary motions of individual bodies.

We have chosen the following labelling of transformation matrices of elementary motions: $\boldsymbol{T}_{Z1}(x)$, $\boldsymbol{T}_{Z2}(y)$, $\boldsymbol{T}_{Z3}(z)$ for translation along the axes x, y, z respectively $\boldsymbol{T}_{Z4}(\varphi_x)$, $\boldsymbol{T}_{Z5}(\varphi_y)$, $\boldsymbol{T}_{Z6}(\varphi_z)$ for rotation round the axes x, y, z respectively.

Equation (1) is an effective notation for study of simultaneous motion, especially of spatial mechanisms which in most cases represent industrial robots. It is also suitable for subsequent numerical solution.

There are shown the locations of the generalized coordinates q_1*, q_2*, …, q_n*. The individual generalized coordinates for all model links form the vector of generalized coordinates of the manipulator mechanism. The position of the point M of the end effector is also indicated. The matrix notation described in the previous chapter is applicable in the following problem analysis. It is practical to describe the relative position of the model links using a set of local coordinate systems. The indicated generalized coordinates are defined using these local coordinate systems. They represent the relative rotations or translations in the respective links of the model.

We can describe any shape of a manipulator model using the transformation matrices of elementary motions [5,8]. In our case a set of motion equations is assembled for the model in Figure 1. The assembled set of equations of motion is then solved using numerical methods. Using the rule of homogeneous transformation between two coordinate systems we define a transformation matrix between the nth local coordinate system and the coordinate system of the base 0 in the form (3):

$$\boldsymbol{T}_{0n}(q_1^*, \ldots, q_n^*) = \boldsymbol{T}_{01}(q_1^*)\boldsymbol{T}_{12}(q_2^*)\ldots\boldsymbol{T}_{n-1,n}(q_n^*) \tag{3}$$

Where:

$$\boldsymbol{T}_{01} = \boldsymbol{T}_{B2}(a)\boldsymbol{T}_{B1}(\xi_{01}) \tag{4}$$

$$\boldsymbol{T}_{12} = \boldsymbol{T}_{B5}(\beta_{12}) \tag{5}$$

$$\boldsymbol{T}_{23} = \boldsymbol{T}_{B2}(b)\boldsymbol{T}_{B6}(\beta_{23}) \tag{6}$$

$$\boldsymbol{T}_{34} = \boldsymbol{T}_{B1}(c)\boldsymbol{T}_{B6}(\beta_{34}) \tag{7}$$

$$\boldsymbol{T}_{45} = \boldsymbol{T}_{B1}(d)\boldsymbol{T}_{B6}(\beta_{45}) \tag{8}$$

Point M position:

$$\bar{r}_{5M} = [e, 0, 0, 1]^T \tag{9}$$

Initial model configuration is described by constant transformation matrices of elementary motions. They set the initial position of the model by applying a constant rotation or translation in the respective link. Transformation matrix of each link with one degree of freedom is given by the product of two matrices, a constant and a variable matrix. Derivatives of transformation matrices of elementary motions can be replaced by a product of the respective transformation matrix and a matrix differential operator as described in more detail in [6-8].

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3 Computer simulation

The algorithms for dynamic analysis are used in software for simulation of the dynamics of bound systems [1-4]. One of them is MSC Adams. We used it to design and simulate a mobile service robot as outlined in Figure 1. In Figure 2 is shown the 3D model compilation. Modelling elements and procedures for the creation of bodies and their kinematic bonds were used in the Adams software. After proposing the model the functionality is verified and the simulation is started Figure 2 [8-10].

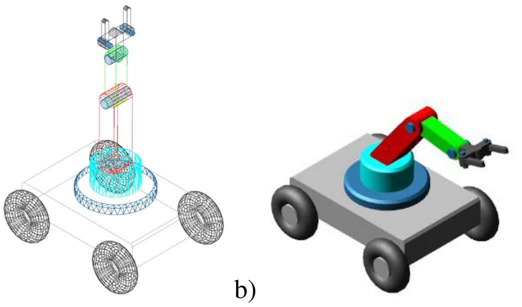

Figure 2 a)-b) Model of the manipulator in MSC Adams/View

The service robot has 5 degrees of freedom of motion. We simulated the model motion in structured environment performing prescribed operations (Figure 3) [11-16].

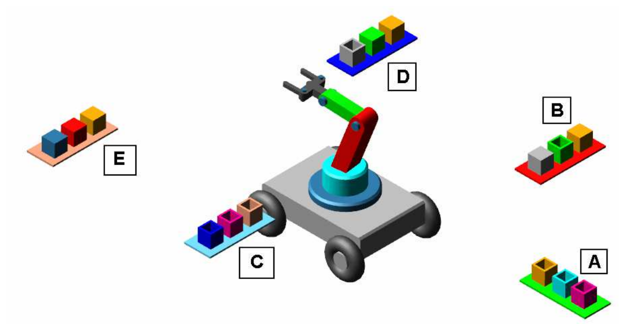

Figure 3 Mobile robot in structured environment with the designation of places A – E to perform the operations

The trajectory in the spatial view of the end effector in structured environment is shown in Figure 4.

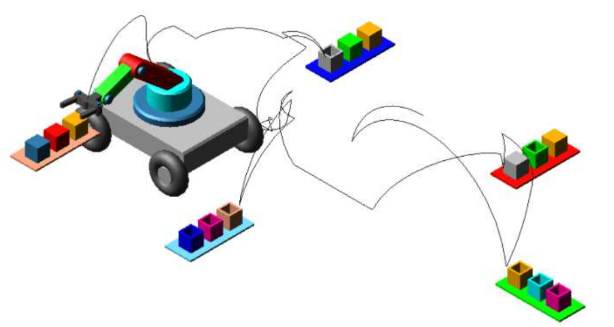

Figure 4 Window of the MSC Adams/View software with trajectory of the end effector in the spatial view

The progression of position (top view) of the end effector are shown in Figure 5.

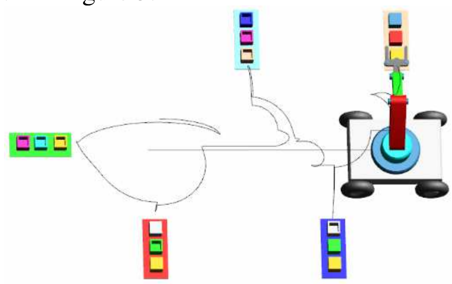

Figure 5 Trajectory of the end effector – top view

Interactive simulation and visualization allows comfortable simulation of the model, model modifications and visualization of results. The graphs of output variables enable viewing the current values of the measured variables in real time during the actual simulation and its visualization (Figure 6).

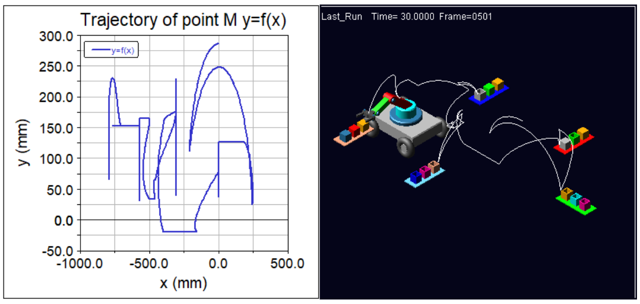

Figure 6 The animation of the simulation and displacement of the end-effector y=f(x)

It is also possible to display the model in its current state and print the results prepared in this way. The postprocessor is an integral part of the computer prototype modeling process and is a very convenient tool for creating, processing, editing and presenting simulation results in the form of graphs [5,8,17]. Simulation output can also be created in AVI format.

4 Resulting kinematic parameters

The resulting graphs are in the following pictures. The values of the calculated variables are displayed in a graphical form with the postprocessor in Figure 7 to Figure 9.

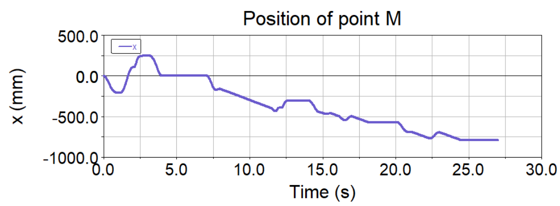

Figure 7 The graph of the x position of point M

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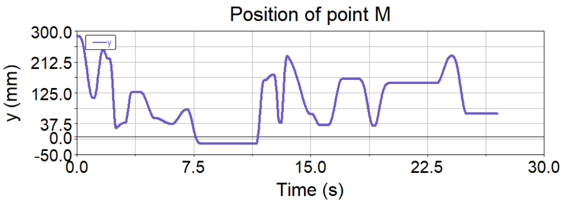

Figure 8 The graph of the y position of point M

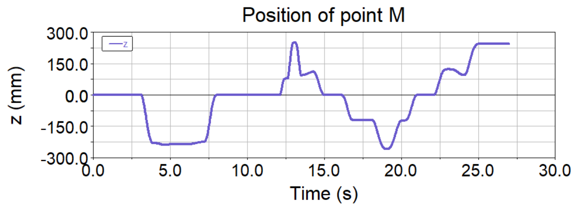

Figure 9 The graph of the z position of point M

The graph of the trajectory of the point M are shown in Figure 10.

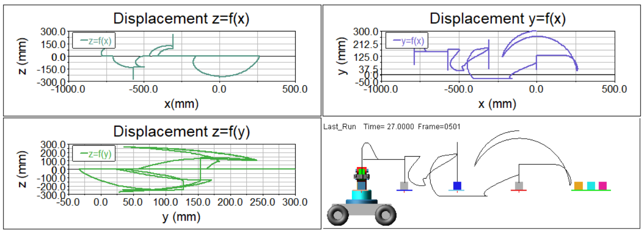

Figure 10 The graph of the trajectory z=f(x), y=f(x), z=f(y) and trajectory front view

The obtained graphs of the actual motion during the motion along the trajectory shown in Figure 10 indicates a suitably designed and functional end-effector position control system.

5 Conclusions

MSC Adams works with a 3D model. The advantage is the possibility to simulate the motion of the prototype model and its control in the program environment and verification of the functionality in the form of 3D visualization. Based on the results obtained from the simulation it is possible to build a real model and design the drives. Based on the results of the simulation it can be stated that the proposed motion in joints is functional during the motion of the manipulator in structured operating environment. Simulation software is a suitable tool for design, saving time and resources. It is also suitable for detailed research and investigation of mechanical systems in practice.

We outlined the process of dynamic analysis of spatial open kinematic chains using the theory of matrices of elementary motions. Movement characteristics of individual kinematic pairs - position, velocity and acceleration at certain time intervals were determined. The benefit of the work is also didactic. Particularly in the field of Applied Mechanics and Mechatronics the presented process offers the possibility of practical application of matrix algorithms for automated generation of mathematical models. These provide the theoretical base for further analysis by existing software and also the possibility to develop more specialized software tools. These procedures are used in software tools which make dynamic analysis and optimization of complex mechanisms more effective.

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MODELLING OF DYNAMIC SYSTEMS IN STATE SPACE

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Keywords: state space, modelling, dynamics systems

Abstract: This paper deals with the solution of dynamical systems in state space. Complicated differential equations are converted into a simpler form by using state variables in vector matrix. It is used for multi-input and multi-output systems, and the solution is performed using matrix notation. It describes systems with complex internal structure. It allows state models to be manipulated using matrix calculus. Systems described by a state model are characterized by the fact that it is easier to design state control for them.

1 Introduction

Classical control theory and the methods we have used so far are based on a simple description of the input and output of a system, usually expressed as a transfer function. These methods use no information about the internal structure of the device and are limited to systems with one input and one output, where we have seen only limited control of closed-loop behaviour using feedback control.

Modern control theory solves many of the constraints using a much richer description of the dynamics of the devices. The trend in engineering systems is towards greater task complexity, especially due to the requirements of complex tasks and good accuracy. Complex systems may have multiple inputs, multiple outputs, and may be time-varying. Due to the need to meet increasingly stringent performance requirements of control systems, the increase in system complexity, and easy access to computers, modern control theories are an approach to the analysis and design of complex control systems. This new approach is based on the concept of state. The state concept itself is not new, as it has been around for a long time in classical dynamics and other fields [1-7].

2 State space representation

A model is a mathematical representation of a physical, biological or information system. Models allow us to predict how a system will behave. In this text we will be interested in models in the so-called state form, where phenomena do not happen instantaneously, e.g., the speed of a car does not change instantly when the pedal is pressed, nor does the temperature in a room change instantly when the air conditioning is turned on.

In corporate systems, increasing research funding for a project will not increase returns in the short term but may increase them in the long term (if it is a good investment). These are all examples of dynamic systems whose behaviour changes with time. Another perspective on dynamics comes from electrical engineering. The prototype of such a problem was the description of electronic amplifiers. It was natural to view an amplifier as a device that transforms input voltages into output voltages, neglecting the internal details of the amplifier.

This resulted in an input-output view of systems. Dynamic systems can be viewed in two ways: an internal and an external view. The internal view attempts to describe internal regularities and comes from classical mechanics. The prototype of such a system was the description of the motion of the planets. For this problem it was natural to give an overall characterization of the motion of all the planets. This requires a rigorous analysis of the action, gravitational action, and relative positions of the planets in the system. The two different views were merged into a control theory. Models based on the internal view are called internal descriptions, state models, or white box models. Models based on the external view are called external descriptions, input-output models, or black box models.

2.1 State variables

The state variables of a dynamical system are the variables forming the smallest set of variables that determine the state of the dynamical system. If at least n variables $x_1, x_2, ..., x_n$ are needed to completely describe the behavior of a dynamical system such that once the input is given for $t \geq t_0$ and the initial state at time $t = t_0$ is specified, the future state of the system is completely determined, then such n variable set is a state variable.

State variables need not be physically measurable or observable quantities. Variables that do not represent physical quantities that are neither measurable nor observable can be selected as state variables. Such freedom in the selection of state variables is an advantage of state methods. In practice, however, it is convenient to choose an easily measurable quantity on the state variables, if at all possible, because optimal control of the control laws will require feedback from all state variables with a suitable value.

2.2 State equation

In state space analysis, we are concerned with three types of variables that are involved in the modelling of dynamical systems: input variables, output variables, and state variables. The state system representation for a given system is not unambiguous, except that the number of state variables is the same for any of the different state representations of the same system.

Suppose also that there are r inputs $u_1(t), u_2(t), ..., u_r(t)$ and m outputs $y_1(t), y_2(t),..., y_m(t)$. We define the n outputs of the integrators as state variables: $x_1(t), x_2(t),..., x_n(t)$.
The system can be described by the equations:

$$\dot{x}_1(t) = f_1(x_1, x_2, ..., x_n;\ u_1, u_2, ..., u_r;\ t)$$
$$\dot{x}_2(t) = f_2(x_1, x_2, ..., x_n;\ u_1, u_2, ..., u_r;\ t)$$
$$\dot{x}_n(t) = f_n(x_1, x_2, ..., x_n;\ u_1, u_2, ..., u_r;\ t) \quad (1)$$

Outputs $y_1(t), y_2(t), ..., y_m(t)$ are defined as:

$$y_1(t) = g_1(x_1, x_2, ..., x_n;\ u_1, u_2, ..., u_r;\ t)$$
$$y_2(t) = g_2(x_1, x_2, ..., x_n;\ u_1, u_2, ..., u_r;\ t)$$
$$y_m(t) = g_m(x_1, x_2, ..., x_n;\ u_1, u_2, ..., u_r;\ t) \quad (2)$$

Then we write equations (1) and (2) :

$$\dot{x}(t) = f(x, u, t) \quad (3)$$
$$y(t) = g(x, u, t) \quad (4)$$

where equation (3) is the state equation and equation (4) is the output equation. The vector functions f and g involve time t and such a system is called a time-varying system.

If equations (3) and (4) are linearized about the operating state, then they have the following linearized state equations and output equations:

$$\dot{x}(t) = A(t)x(t) + B(t)u(t)$$
$$y(t) = C(t)x(t) + D(t)u(t) \quad (5)$$

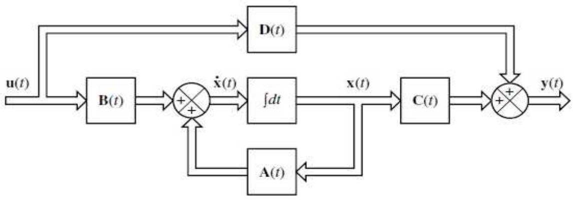

Figure 1 Graphical representation of state equations [1]

Matrix:
A (t) system matrix,
B (t) input matrix,
C (t) output matrix,
D (t) feedforward matrix.

3 Computer simulation of dynamic systems

A simple mechanical oscillator will be used as a first example to express the state description (Figure 2). Consider a mechanical system consisting of a body of mass m fixed by a spring of stiffness k against a rigid frame.

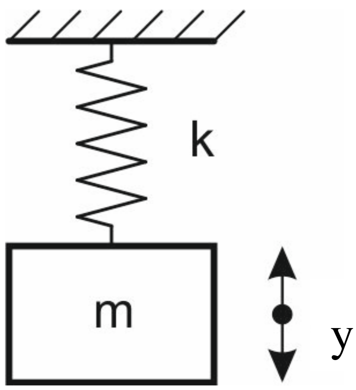

Figure 2 Mechanical oscillator

The equation of motion of the system is:

$$m\ddot{y}(t) + ky(t) = 0 \quad (6)$$

We define the state variables $x_1(t)$ and $x_2(t)$ as:

$$x_1 = y$$
$$x_2 = \dot{y} \quad (7)$$

If we perform the derivation of the state variables, then it is possible to write:

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = -\frac{k}{m}x_1 \quad (8)$$

The dynamic system is not excited by an external force, the initial condition is given to the initial condition x_{10}=0.3m.

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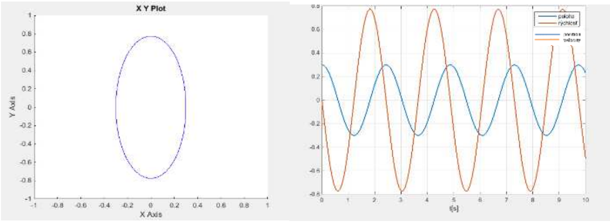

Figure 3 State trajectory and plot of results kinematic parameters

Consider the mechanical system p in Figure 4, which consists of a mass m, a spring k and a damper b on which a force f(t) acts. We assume that the system is linear.

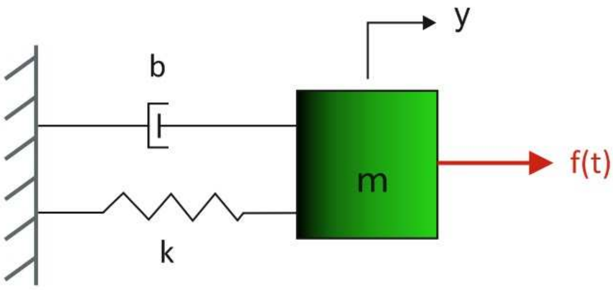

Figure 4 Second-order dynamic system

The external force f(t) is the input to the system and the displacement of mass y is the output. This system is a system with one input and one output and has one degree of freedom. The equation of motion of the system is:

$$m\ddot{y} = f(t) - f_b - f_k$$
$$m\ddot{y} = f(t) - b\dot{y} - ky$$
$$m\ddot{y} + b\dot{y} + ky = f(t) \qquad (9)$$

The second-order differential equations describes the system, then two simultaneous, first-order differential equations are required along with two state variables. We define the state variables $x_1(t)$ and $x_2(t)$ as

$$x_1(t) = y(t)$$
$$x_2(t) = \dot{x}_1(t) = \dot{y}(t) \qquad (10)$$

Equation (10) can be solved for the state variables. For a linear, time-invariant, second order system with a single input, the state equations could take on the following form. Furthermore, it is possible to write:

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = = -\frac{k}{m} x_1 - \frac{b}{m} x_2 + \frac{1}{m} f \qquad (11)$$

Where x1 and x2 are the state variables. There is a single output, the output equation cold take on the following form:

$$y = x_1 \qquad (12)$$

The coice of state variables for a given system is not unique. The requirement in choosing the state variables is that they be liearly independent and that a minimum number of then be chosen.

In the standard form it is possible to write:

$$\dot{x} = \boldsymbol{Ax} + \boldsymbol{Bu}$$
$$\boldsymbol{y} = \boldsymbol{Cx} + \boldsymbol{Du}$$

In matrix form, equations (11) and (12) can be written:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{k}{m} & -\frac{b}{m} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix} f$$
$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \qquad (13)$$

where

$$A = \begin{bmatrix} 0 & 1 \\ -\frac{k}{m} & -\frac{b}{m} \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix}$$
$$C = \begin{bmatrix} 1 & 0 \end{bmatrix} \quad D = 0 \qquad (14)$$

Plot of results kinematic parameters such as the position and velocity of the mass is on Figure 5.

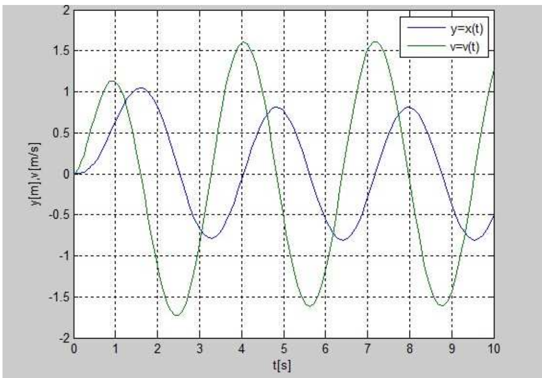

Figure 5 Representation of position x(t) and velocity v(t)

By examining a large number of dynamical systems, it was found that the shapes of the trajectories of the systems can take many different forms. Some of them are convergent, monotonous or periodic to some limit of what can be a point or a set of points (a circle). We are talking about a stable system. On the x-axis is represented the state variable x_1, i.e. the position, and on the y-axis the state variable x_2, i.e. the velocity of the mass m (Figure 6).

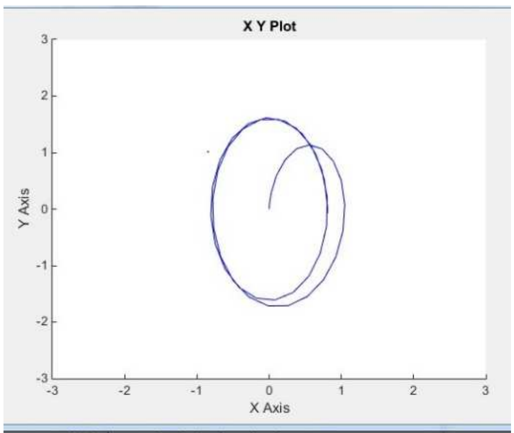

Figure 6 State trajectory of mechanical system

In the next case, consider the mechanical system shown in Figure 7, which consists of two bodies of masses m_1 and m_2 fixed in series by means of three springs of stiffness k_1, k_2 and k_3 on a rigid frame. An excitation force F acts on the body of mass m1 in the positive direction of the x_1 axis.

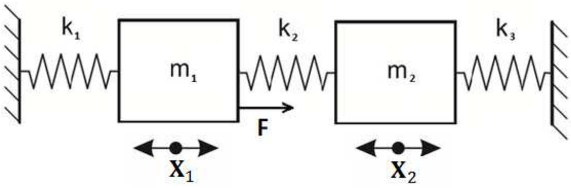

Figure 7 Two-mass dynamic system

In this case we get two equations of motion of the form:

$$m_1\ddot{y}_1 = -k_1y_1 + k_2(y_2 - y_1) + F$$
$$m_2\ddot{y}_2 = -k_2(y_2 - y_1) + k_3y_2 \qquad (15)$$

After modification we get the shape:

$$\ddot{y}_1 = (-k_1y_1 + k_2(y_2 - y_1) + F)/m_1$$
$$\ddot{y}_2 = (-k_2(y_2 - y_1) + k_3y_2)/m_2 \qquad (16)$$

Choosing state variables:

$$x_1 = y_1$$
$$x_2 = \dot{y}_1$$
$$x_3 = y_2$$
$$x_4 = \dot{y}_2 \qquad (17)$$

Derivations of state variables can be written:

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = -\frac{k_1x_1}{m_1} + \frac{k_2(x_3 - x_1)}{m_1} + \frac{F}{m_1}$$
$$\dot{x}_3 = x_4$$
$$\dot{x}_4 = -\frac{k_2(x_3 - x_1)}{m_2} + \frac{k_3x_3}{m_2} \qquad (18)$$

Equation of state of the system:

$$\dot{\boldsymbol{x}} = \boldsymbol{Ax} + \boldsymbol{B}u \qquad (19)$$

Then we write the equations (18) in matrix form:

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{bmatrix} = \begin{bmatrix}0 & 1 & 0 & 0\\ -(k_1+k_2) & 0 & k_2 & 0\\ 0 & 0 & 0 & 1\\ k_2 & 0 & (k_2-k_1) & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\end{bmatrix} + \begin{bmatrix}0\\ 1\\ 0\\ 0\end{bmatrix}F \qquad (20)$$

Plot of results kinematic parameters such as the position and velocity of individual masses can be seen on the Figure 8.

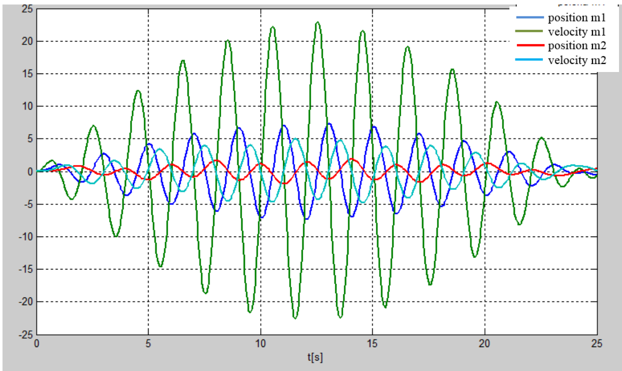

Figure 8 Position and velocity of the mechanical system in Matlab

4 Conclusions

The aim of the paper was to define a state space description of dynamical systems. and then apply it to examples of mechanical systems. Second-order differential equations were expressed and written in the form of vector matrices using state variables The state description of a dynamical system can describe systems with multiple inputs and outputs and systems with complex internal structure. The results of the solutions of the mechanical systems were obtained using Matlab/Simulink.

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DESIGN OF AN AUTOMATED SYSTEM FOR MEASURING CAR BODIES

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Keywords: automation, measurement system, 3D scanners

Abstract: The work presents and describes selected measurement methods of bodywork geometry. The principle of operation of 3D scanners has been described together with their application in the implementation of vision measurement systems in the automotive industry. The paper also presents methods used to automate measurements in diagnostics and vehicle repair processes. In addition, the work presents the concept of a measurement system which combines the ideas of vision measurements and mechanical repair devices.

1 Introduction

The current automotive market generates the demand for a fast and efficient technological process to be implemented both in manufacturing and measurement technologies. Product quality verification is desired at every stage of production. It is necessary to quickly respond to changing process parameters to eliminate further processing of defective semi-finished products. The answer to the above requirements is to implement vision measurement and control systems [1].

Vision techniques result from the synergy of optics, photography, electronics, mechanics, control theory, mathematics, and computer science [2]. Together they enable control of the quality of manufactured products from semi-finished products to finished products. Quality control involves obtaining a product image, which is then processed to identify any irregularities or is compared to a reference product. The intensity of production imposes the necessity of using high-speed devices, including effective methods of image analysis [3]. Currently, industrial vision systems are most frequently used to quality control of final products. The global trends show that they are used at every stage of production, inter alia, to supervise and control basic process parameters, which significantly prevents the production of defective products [4].

Vision systems may be classified into four basic application groups [5]:

- vision measurements – to obtain photometric or geometric measurement of products (e.g., to determine the dimensions, position and orientation, order of parts, supervision, etc.),
- vision inspections – in quality control, by photometric or geometric measurement of a given product,
- vision identification – due to the interrelations of objects remaining in the field of the view of a camera, the values of parameters are obtained based on their images,
- machine guidance – obtaining a geometric (full or partial) description of the scene to safely plan and control the movement of the machine (e.g., robot).

In quality control systems, a non-contact control of the product parameters is frequently required (e.g., geometry, roughness, shape errors, etc.). Often, due to harmful working conditions or difficult availability of the inspection location, machine is the only solution. Vision systems also allow the generation of reports enabling the assessment of the quality of significant technological processes in the product production processes. They are particularly useful in production based on certified quality management systems [6-8]. The above-mentioned properties contribute to the increasing popularity of automated vision systems for quality control [9-11]. With the proliferation of computer technologies, including matrix image converters, vision systems have been successfully used in the automotive industry. Automation of the process of bodywork measuring with the use of

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cameras and 3D scanning technologies significantly shortens the process of vehicle production, and thus translating into increased production efficiency. A modern, visual method of measurement has supplanted previously used technologies based on analogue devices.

New methods and measurement concepts are currently being developed and implemented, an example of which is a reverse engineering technology or coordinate measuring technology. Reverse engineering relies on digitizing the geometry of a real object. The result of this process is the digital form of the model, which constitutes the basis for further technological and constructional works as well as analyses. A coordinate measuring technique is characterized by measurement procedures based on coordinate values of measuring points. It enables the determination, with a relatively high accuracy, of dimensions of spatially shaped machine parts. Implementation tools for both processes are 3D scanners and measurement systems created with their use [8,12,13,15]. Two basic groups of scanners are distinguished: non-contact scanners and contact scanners [12-14]. The division of existing scanners is shown in Figure 1.

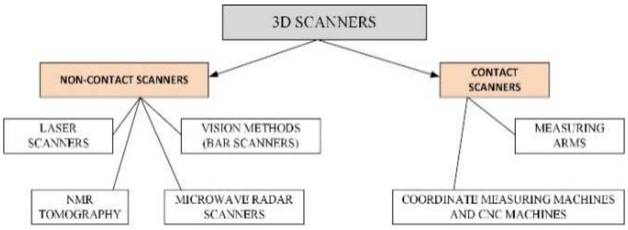

Figure 1 Division of 3D scanners

The aim of this study is to indicate possible utilization of vision systems in the repair processes of self-supporting load-bearing structures of vehicles. The modern vision systems were analysed and a concept of a structure of a system for measuring the geometry of bodywork for the needs of vehicle construction and repairs was developed.

2 The use of selected vision systems in bodywork designing

The shape of the bodywork significantly affects not only the aesthetics of the vehicle itself, but above all, its technical parameters. It includes all safety issues and questions related to the quality assurance system [16]. The external appearance of a vehicle is affected by the surface and the spatial form of the bodywork. Smoothness (streamlines) of the surface and lines dividing the bodywork into individual elements determine not only aesthetic values, but also affect aerodynamic properties. In the process of constructing the bodywork, there is a need to create specific surfaces and then to dimension them accurately. Currently, there are two methods of constructing vehicle bodywork: a traditional method and an (intensively developing) computer method. The first method involves developing a physical bodywork model, and then the construction documentation is prepared. The second method is based entirely on the building of virtual 3D models [17].

Three main factors are taken into account in the design of self-supporting bodywork:

- manufacturing costs,
- functionality,
- unladen mass of the bodywork, which determines the resistances of vehicle movement and directly affects the fuel consumption.

Automation of a construction process is primarily the introduction of computer technology to every stage of design. The basis for elaboration of a computerized documentation is a precise digital image of the surface performed with the use of one of the CAD systems. The quality of the developed structure can be checked without referring to a real model. Thanks to this, it is possible to correctly create original and sophisticated shapes. In particular, the digital recording of the surface, obtained thanks to the digitalization of the reduction models, eliminated the long-lasting and costly stage of mastermodel construction [18,19].

3D scanning employed in the process allows quick and accurate formation of three-dimensional documentation of physical objects. The result of the scan is a complete digital model, which can later be edited and processed by CAD/CAM programs as well as prototyping, visualization and animation programs. Thanks to the digitalization of reduction models with the use of scanners emitting structural light, the whole cycle of bodywork formation is significantly shortened. This is due to the shortening of the surface shaping time, the rapid digital recording of its parameters, the ease of assessing the quality of the developed surface and the ease of introducing any corrections or modifications. The time needed for the preparation of drawing documentation is also significantly limited. The documentation is now acquiring a secondary importance since a digital record of the surface forms the basis for the next stages of work. Based on this record, calculations of elements strength (MES) may be performed, and programs for numerically controlled machine tools or pressing tools (both of which may be used in production of a final model) may be developed. After the “electronic” assembly of individual elements, construction nodes or the whole bodywork, it is possible to test the bodywork in terms of safety, aerodynamics, or acoustics with the use of computer simulations. Thus, the so-called virtual model is formed [19-25].

One of the systems supporting the digitization process is the Bruckmann's NaviSCAN3D scanning system. The main feature of this system is the use of a set of cameras that track the position of the scanner in the measuring space and the use of a spatial reference frame (as an element of the scanner head). The solution works well in the case of measurements of large elements, eliminating the process of preparing the measured element before the measurement

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(applying reference points and using the photogeometry system). The system allows full automation of the digitization and measurement process. Properly configured measuring system [26-29] enables:

- scanning of aluminium and galvanized steel elements without applying antireflection coatings. The scanning system collects accurate data from highly reflective areas,
- scanning with high accuracy of both the surface of the element and the edge of the holes, leaving the cutting lines,
- application of a robot: the limited absolute positioning accuracy of the robot has been compensated by a large volume tracking system, and verification of each scanner position while setting the process parameters. Such defined positions of individual views were the basis for the next measurement series,
- the process time significantly shortened.

Figure 2 - Figure 4 present the formation of digital documentation and the archiving process on the example of a vehicle door prototype. Figure 2 shows the NaviSCAN 3D scanner installed on the KUKA industrial robot [29].

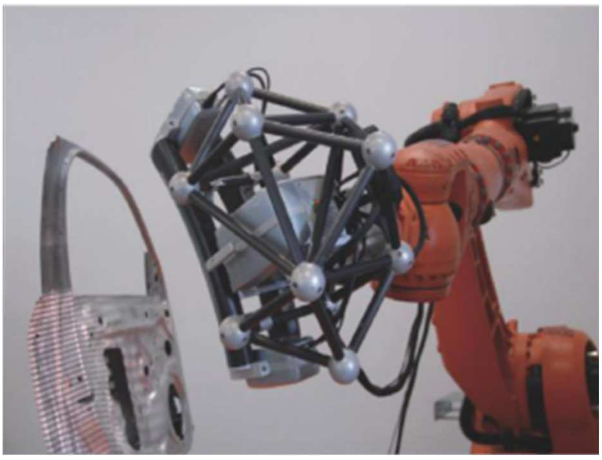

Figure 2 The process of digitization of an element with a bar scanner

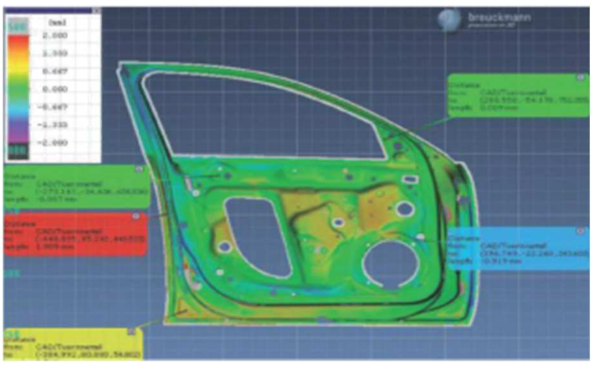

Figure 3 Image generated by the system. A map of deviations – SCAN vs. CAD

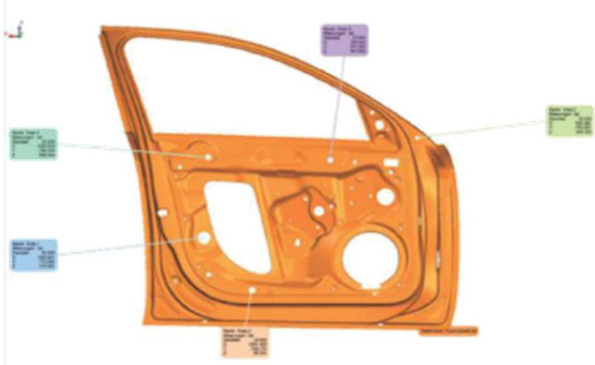

Figure 4 Verification of the coordinates of the position of the centres of selected holes

Digital documentation and archiving of prototype elements of bodywork allow for [30]:

- fast and precise 3D data generation by the NaviSCAN3D system,
- full digitization of an element in a few minutes, the average scanning time is about 15 minutes,
- full automation of the measurement process – human intervention needed only to fix the measured element on the table,
- automatic generation of measurement reports thanks to the use of advanced tools for data inspection (Rapidform, Polyworks).

The measuring systems using scanners that emit structural light outside the measurement are ideal for product quality control processes thanks to the fact that they allow quick comparison of the manufactured element with the project, which, in turn, enables detection of manufacturing errors, comparison of cross-sections, or else the identification of areas exceeding the assumed tolerance [31-35]. Digitization and quality control improve the product development and optimization processes and the production preparation.

The current bodyworks created regarding safety requirements are supplied with energy-intensive zones, which are subject to strong deformation during a collision. Bodywork repairs of this type are more complex. They can be divided into two categories:

- the first, which includes the replacement of permanent elements of the bodywork structure,
- the other, consisting of straightening the structure and replacing the damaged parts or entire welding assemblies forming the bodywork [36].

The first type of bodywork repairs consists in replacing external equipment elements, external coating or covers and local bodywork repairs which restore the original shape of the element.

The second type includes the repair of medium and serious damage to the bodywork supporting structure. Repairing such damaged bodywork requires replacing some elements of the structure or even whole welding assemblies and restoration of the proper bodywork

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geometry. The geometry of the body is connected with the correct mutual position of many characteristic points related to fastening of mechanical assemblies such as the vehicle suspension, travel gear and drive system. Improper geometry of the bodywork directly affects the safety of the vehicle [37-39].

The latest equipment solutions include the proper repair and measurement systems equipped with a computer and electronic sensors. Important features of the system include the simple service and their versatility enabling the repair of bodyworks of various makes and types [40].

The diagnosis, measurement and repair of bodywork should include [41,42]:

- setting and fixing the bodywork to the frame,
- levelling the bodywork on the frame,
- finding a few characteristic points (minimum 3÷4) that were not displaced during the collision,
- replacement of damaged elements and systems,
- disassembly of external coating and covers,
- stretching (straightening out) damaged elements of the bodywork and bringing them to such a form that the remaining control points were in the correct places, according to documentation provided by the vehicle manufacturer,
- checking the position of all characteristic fixing points of mechanical components (fixing them to the bodywork),
- replacement of damaged elements and systems (with the new ones),
- assembly of the external coatings and covers.

A list of control dimensions characteristic for a given body (measuring points) is included in the company's repair manual or specialist literature. Some of these dimensions refer to fastening mechanical assemblies while others determine the geometry of the bodywork associated with the assembly of windows, covers and other elements.

3 Selected modern measuring and repair systems for vehicle bodywork

Mechanical measuring devices usually have a modular construction [43]. Figure 5. presents such a device made by Autorobot, a Finnish company [44].

Figure 5 Mechanical device made by Autorobot, used in bodywork repairs. 1 – longitudinal beams, 2 – symmetrical measuring bridge, 3 – independent measuring bridge, 4 – measuring heads, 5 – protectors, 7 – movable gate, 8 – boom

The basic element of the device is a movable gate (7) placed on the lower longitudinal beams (1). The gate may move along the beams to the points which are to be measured. The construction of the Autorobot mechanical measuring device includes symmetrical measuring bridges connecting longitudinal beams. The special booms, with measuring heads on them, are attached to the movable gate and to the measuring bridges. The internal space of the device is 1890 mm high and 2070 mm wide. The length of the booms is adjustable from 0.5 ÷ 4 meters. Measurement with a mechanical measuring device consists in reading three coordinates of the measured point i.e., the coordinate of height, width and length. The Autorobot measuring system is equipped with data files (on disk or on the Internet) containing information about the location of measurement points for various vehicle brands. This allows the use of the measuring system during repair work with the possibility of evaluating deviations from the factory data [44].

Figure 6 shows sample measurement cards [44]. Thanks to the large database, it is possible to measure all chassis structures including assembly points, McPerson columns, suspension frame, etc.

Figure 6 Examples of measuring cards (in paper form and on CDs) containing base points

The Autorobot system is equipped with measuring data for the bodywork and chassis of 2000 types of car brands. The data is updated and supplemented every quarter. A mechanical measuring device can be used both to control the straightening process and to check the results of repairs.

The Swedish company Car-O-Liner offers electronic measuring devices: Car-O-Tronic Classic, Vision and Vision X3. The Car-O-Tronic Classic is a computer measuring system that supports the entire repair process – from damage analysis to after repair checks and the formation of the repair documentation. This system allows the measurement of all base points of the bodywork and chassis using a simple jack, a channel or directly on the floor. The discussed Car-O-Tronic Classic device is shown

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in Figure 7 (during measurements of a car being repaired) [45].

Figure 7 Electronic Car-O-Tronic Classic measuring system during bodywork repair

The measuring system consists of a measuring bridge that acts as a carrier for the rest of the system's measuring elements. The measuring bridge is equipped with guides with measuring rulers with attached micromarkers. They are all mounted on a frame fixed on a scissor lift. The module with the measuring head, which is used to read the position of the measuring points, moves along the measuring bridge. The module is shown in Figure 8 [46,47].

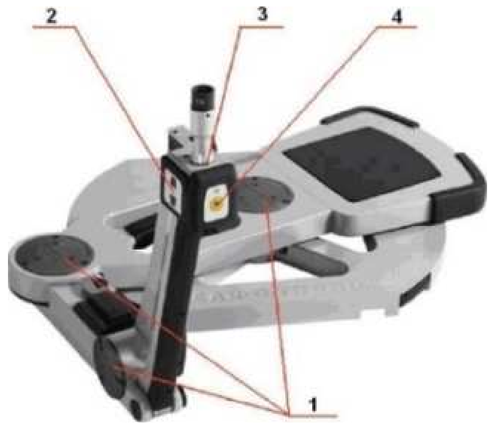

Figure 8 Car-O-Tronic measuring head, where: the measuring module consists of three rotary joints marked as: 1 – joints providing information in a continuous cycle. The positions are read three times per minute, 2 – the communication system (included in module 2) with a central unit is wireless. The exchange of measuring tips of various lengths, angular settings and diameters is carried out using a quick connector, 3 – the module is equipped with a socket (4) for connecting external devices.

A replaceable measuring tip is attached to the measuring head. The system also includes a data sheet (base points) and software enabling real-time tracking of the tip's movement relative to the point given in the database. Data from the head is sent wirelessly to the central unit. The position of the measuring tip relative to the position required for a given vehicle type (when measuring characteristic points) can be observed on the monitor screen (Figure 9) [49].

Figure 9 Screen with a visible measuring point position.

In the most advanced version, the device is equipped with automatic centring systems and a base of photographs of elements with marked measuring points for each of the available car models. The so-called measurement cards (Figure 10) are developed in cooperation with car manufacturers (over 15 500 measuring cards of car models in the database) [47]. Data update is performed quarterly. With the help of an electronic system, repair documentation can be issued (prints in graphical form or containing magnitude values, before and after repair).

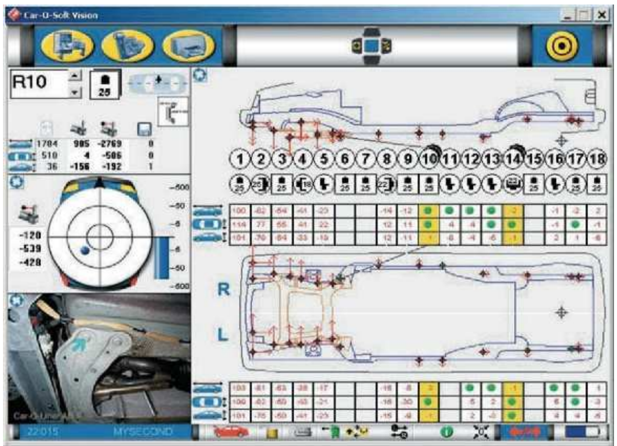

Figure 10 Screen with a visible measuring point position measurement card and base points

4 The concept of a visual measuring system supporting vehicle bodywork repairs

The basic assumption of the conducted research was to perform a detailed analysis of the possibility of connecting a repair frame with a vision system enabling full

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dimensional control in real time of the process of straightening of damaged elements of bodywork. An attempt was also made to develop algorithms for elements straightening, considering the strength parameters of the materials used in their production [49].

The system was built using the RN-4300 Standard repair frame manufactured by Zakład Mechaniki Maszyn from Trzcianka near Piła (Figure 11). The frame is intended for repairs of self-supporting bodyworks of passenger cars and delivery vans. It is featured by high stiffness and has well thought solutions for fixing additional equipment. It is well equipped and good value for money [49].

Figure 11 Repair frame RN Standard

The frame consists of the following elements and features the following technical parameters:

- the frame skeleton is 5500 mm long and 6100 mm wide,
- sliding side arms to attach the jaws,
- hydraulic straightening unit,
- jaws for fixing the bodywork to the frame,
- special attachments for fixing vans and buses.

The frame has an Xpectia FZ3 vision system from OMRON featuring:

1. depending on the model, it is possible to connect from 1 to 4 cameras with a CameraLink-camera interface (with a resolution from 300k ÷ 5M pixels),
2. it is possible to integrate the illuminator with the camera and video system,
3. Data transmission takes place via the RS232C / 422A serial port or the 100BASE-TX / 10BASE-T network interface,
4. it is equipped with 11 analogue inputs and 26 digital outputs,
5. has 4 USB 1.1/2.0 ports for pointing and storing devices,
6. 32 groups of scenes, each group contains 32 scenes.

The structure of the Xpectia FZ3 system is shown in Figure 12.

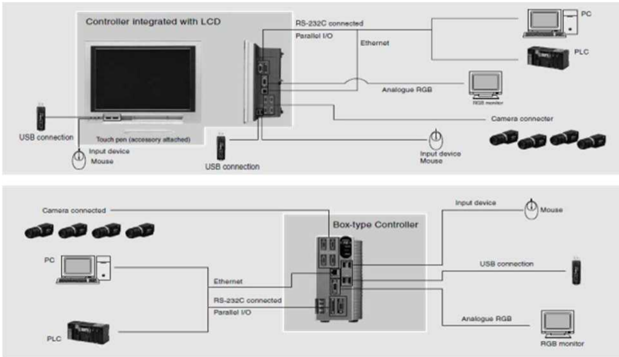

Figure 12 Xpectia FZ3 system configuration

All devices of the vision system were connected to the controller integrated with the touch panel or the box-type controller. Flash memory was used to store more data and measurement settings. For communication with other devices, the Xpectia FZ controllers used the LAN (Ethernet) interface and the parallel port. Measurement data is made available through the embedded FTP server. Xpectia FZ3 devices are equipped with a powerful processor that enables the operation of cameras with a resolution of up to 5 Mpx. The methods of initial data processing (preprocessing) and measurement methods have been introduced. There is a possibility of removing a repeating background pattern from the image. It is also possible to repeatedly search a given pattern on the observed scene, to eliminate trapezoidal distortions or to combine images from several cameras. Integration of images from several cameras into one allows obtaining a larger measurement field. Together with a vision measurement system, the manufacturer provides software that enables relatively simple, intuitive operation.

Before starting the repair process, it is very important to carry out a properly planned calibration of the measurement system.

The calibration of the vision system was based on the Single camera (monovision) method e.g., using the Matlab Camera Calibration Toolbox for Matlab, which allows measuring the distance between three points (three points corresponding to the technique of measuring the position of three characteristic points on a selected surface).

To obtain information about the location of the measurement points, it was first necessary to determine the coordinates (x, y) of the space and then to obtain information on the location of these points in this space. This involved the use of 20 images (sequence of 20 photos from the camera equipped with the CameraLink interface). It was important that all measuring points were in one image.

Figure 13 shows points: P1, P2, P3 representing three measuring points that map the distances between these points in a two-dimensional space. In the canonical system,

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the corresponding points in the image plane of the camera are connected by the so-called epipolar lines.

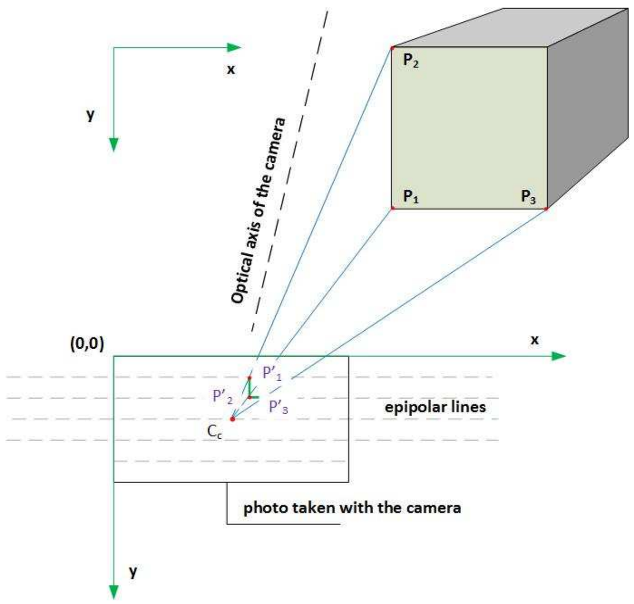

Figure 13 Calibration method of the Xpectia system by using CameraLink camera

Based on the sequence of 20 corresponding photographs taken in the monovision technique, the calibration procedure should first be carried out i.e., the verification of the distance between the measuring points using the Camera Calibration Toolbox in the Matlab package. The average image reprojection error was 0.8 pixels per photo.

Subsequent stages of working with the Xpectia system:

- programming the Xpectia system – preparing a scene (scenes) containing a sequence of function blocks performing selected tasks, the first block of the scene – downloading the image,
- the successive blocks are associated with the processing and recognition of the content, image and the implementation of other tasks,
- each block returns the overall result in the form of OK/NG (correct/incorrect) and individual detailed information specific to it,
- at the end of the scene sequence, the information available from individual blocks can be used to make the final decision and the appropriate response, the information obtained can be displayed in the image preview area and sent to other devices via available interfaces.

Figure 14 shows a diagram of the proposed connection between the repair frame and the vision system.

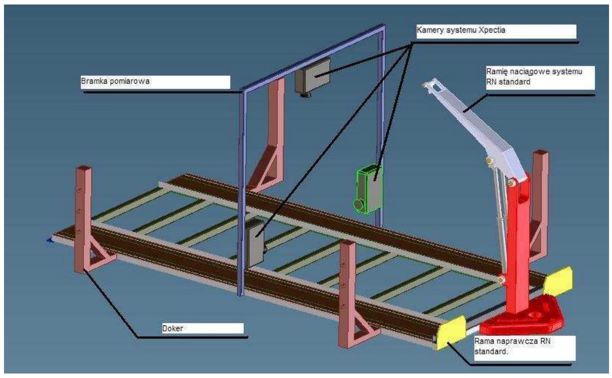

Figure 14 A diagram of a new vision measurement system with a repair frame

The measuring gate has been integrated with the repair frame. There are 3 cameras of the Xpectia system on the gate. They allow the measurement of the geometry of bodywork and chassis during repair work in real-time.

The basic components of the appliance are as follows:

- repair frame with a stretching arm,
- measuring gate with a vision system mounted,
- measuring-control software.

Further work on the advancement of the system is expected to result in developing an algorithm controlling the speed of stretching the repaired structural elements of the vehicle bodywork, since the straightening of elements often results in their excessive and multiple deformations. The excessive and repeated deformations lead to unwanted weakening of the repaired elements and, consequently, of the whole structure. The algorithms controlling the straightening process should consider the characteristics of the material of the repaired elements. The straightening process will be performed automatically and will be fully controlled by feedback force (deformation force) until the factory shape of planes and the positions of reference points are restored.

Most connections in the bodywork structure are made using resistance spot welding. In the repairs, spot welding is often replaced by electric welding. Welding causes thermal deformation of elements and their decarburization. Therefore, also these phenomena need to be included in the straightening control algorithm.

The proposed idea requires many additional experimental studies and analyses. The measurements thus obtained need be confronted against the technical specifications of repaired vehicles – base point maps (provided by the manufacturer). The concept of the developed system is the starting point for construction and research works towards the full automation of works related to the repair of vehicle bodyworks. The proposed concept can significantly shorten the measurement and repair process and improve the quality of repairs performed in repair workshops.

5 Conclusion

The considerations and examples of automation of bodywork measurement process presented allow to formulate the following conclusions:

- Measurement technology has recently evolved mainly due to the development of computer data processing technology.
- Contactless scanners play the predominant role in the vision measurement systems. They allow a relatively short time of data acquisition and relatively low cost of the process, they are used more and more increasingly, mainly in automated manufacturing processes.
- There are differences between the automation of measurement processes for construction and manufacturing purposes on the one hand, and the automation for repair processes on the other hand.
    - In the process of constructing and formation of bodywork, non-contact scanning methods play a considerable role, and in particular the scanning method using scanners emitting structural light is becoming more and more popular.
    - In diagnostics and repair processes, devices with contact-based measurement techniques are preferred.
- Measuring devices can be used in the vehicle diagnostics process. In the case of post-accident damage, they are usually used together with repair frames, because they allow tracking the repair process, giving current information on changes in the bodywork geometry. Analogue instruments, often integrated in measurement systems, are usually used for this purpose.
- The combination of experience in the field of automation of measurement processes practised in manufacturing processes with the automation of measurements of the bodywork geometry used for repair purposes gives a new quality in the technology of vehicle bodywork repairs. An expression of this synthesis is the proposed concept of including real-time measurement in the repair process.
- The proposed solution may be practically applied not only in repair processes, but also in periodic technical inspections of vehicles carried out at vehicle inspection stations. This will certainly increase the effectiveness of the inspection process and will contribute to the safety improvement on public roads.

Constantly increasing quality requirements of manufactured products, especially in the automotive industry, result in the need to use automated control systems characterized by very high accuracy and speed of measurement.

This applies to both manufacturing and diagnostic processes, including post-accident damage repair processes. Diagnostic and repair processes are also subject to increasingly rigorous legal restrictions to ensure greater safety of people using these vehicles in road traffic.

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