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STRATEGY FOR CONTROL OF A HYBRID MACRO-MICRO ROBOT WITH A 5-LINK CLOSED STRUCTURE – AN INVERSE PROBLEM OF KINEMATICS

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Abstract: *The combination of robots for macro and micro operations is necessary for performing a large number of technological operations where macro motions precede finishing high accuracy motions. The basic difference between the two manipulation systems (MS) is the type of actuations used. The present study offers algorithms for solving inverse problem of kinematics (IPK) related to a macro MS without linearizations and IPK for a micro MS which is redundant, having two extra degrees of freedom. Conditions for unidirectionality of the basic links of a micro MS are assumed. A virtual model of a robotized system is developed and presented on the basis of the algorithms designed for solving the IPK. The robotized technical solution can be useful for cell manipulations where high precision and high speed of cell injection are required.*

Key words: *macro-micro actuators, manipulation system, inverse problem of kinematics.*

1. INTRODUCTION

The combination between robots for macro and micro operations is necessary in order to perform a large number of technological operations where macro motions precede the finishing high accuracy ones [1–5]. The basic difference between the two manipulation systems (MS) is the type of actuations used. Universal classical actuating devices (AD) are implemented in a macro MS, while micro motors and actuators that have been rapidly developed in recent years are used in a micro MS. Note that micro motors and actuators are assembled using polarized piezo elements. There are different types of piezo actuators – bimorphic or multilayered, with an operational run of 300 μm and a resolution of several nm [6–12]. Piezo actuator control is performed regarding current or voltage. Their advantages are high dynamics and accuracy which make them suitable to automate processes running in micro and nano ranges. Their disadvantages are the sharply expressed hysteresis and creep of piezo materials [14–22].

For now, the most widely used method of hysteresis linearization is the integration of tenso-transducers as sensors, as well as the integration of inductive and capacitive sensors [23–25]. Piezo actuators are also applied in the development of MEMC devices such as micro-force sensors. Note also the design and development of hybrid robotized translational modules, which integrate step or direct current motors and piezo-actuating elements.

As known, mechanical systems with open and closed kinematic chains (KC) are employed in the development of macro and micro robots. The mechanisms with open kinematic chains are characterized by a simpler structure and simple control of the actuating modules. On the other hand, the realization of the structure of closed chains is not a simple task. The respective control algorithms are more complex, and parallel control of several actuating modules should be executed. Yet, that structure is more reliable having small dimensions and high accuracy. Several robotized solutions in micro and nano manipulation areas are known, but there is no data about a robot automating the process “grip-position”, and in particular – no information about the employment of a 5-link mechanism in micro and nano manipulation processes.

We have performed a detailed kinematic analysis of a hybrid macro-micro robot with a 5-link two-crank closed structure and the direct problem of kinematics (DPK) is solved. The geometrical conditions of full rotation of the two input links are set forth, the accessible spaces for such a MS are outlined, and the transfer functions (TF) of the actuators incorporated into the links are derived assuming that the system linearization is legitimate. Also, the conditions for unidirectionality of macro motions at the end of the cycle and micro motions at the start of the cycle are found. These problems are specific for the DPK [25].

The aim of the present study is to solve the inverse problem of kinematics for a macro mechantronic system without linearization and the one for a micro mechatronic system, which is redundant, with two extra degrees of freedom (DoF). Conditions for unidirectionality of the basic links of a micro MS are taken as optimization conditions. The basic algorithms for designing a control strategy are presented. Results published in [26–28] are used to choose the configuration of a macro MS at the start of a micro operation.

A numerical example is considered on the basis of formulas derived to solve the inverse problem of kinematics. The validation of the theoretical set up is realized by designing a virtual model of the robotized system and performing an analysis of the simulation results found.

2. INVERSE PROBLEMS OF KINEMATICS CONSIDERING A MACRO-MECHATRONIC SYSTEM

A macro-mechantronic system is based on a 5-link mechanism shown schematically in Fig. 1. On macro level, the chain consists of 5 mobile links (1–5) with dimensions l_1–l_5 and angular coordinates φ_2–φ_5. Those whose angular displacements are specified by angles φ_2

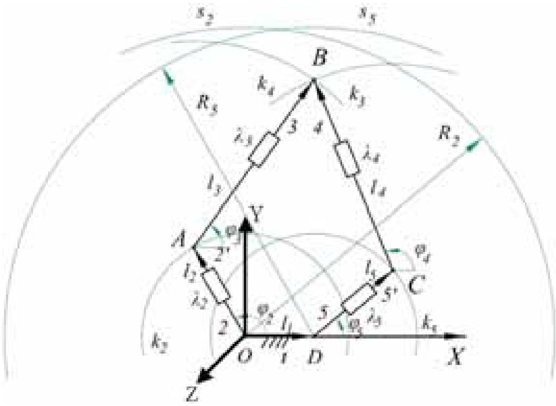

Fig. 1. Two-crank closed 5-link mechanism.

and φ_5, are chosen as active pairs. Note that the angular displacement characterizes a mechanism with 2 DoF. Chain operational space is specified by arcs k_2–k_5, s_2 and s_5. To perform finishing operations in micro and nano ranges, a piezo actuator is integrated in each mobile body (λ_1–λ_4).

Coordinates x and y of the point B are given for a IPK (note that velocities can also be specified), and a corresponding configuration of KC is sought. More specifically, we look for the parameters of the actuating devices (AD) – angle φ_2 and the respective velocities. Point B is the cross point of the circles

$$(x - x_A)^2 + (y - y_A)^2 = l_3^2, \quad (x - x_C)^2 + (y - y_C)^2 = l_4^2, \tag{1}$$

where

$$x_A = l_2 c\varphi_2,\ y_A = l_2 s\varphi_2, \quad x_C = l_1 + l_5 c\varphi_5,\ y_C = l_5 s\varphi_5. \tag{2}$$

Here one can consider either the nominal values of the dimensions of links l_i or dimension increase after actuator activation. After elementary transformations, we get the following equations via (1) and (2)

$$x^2 + y^2 - 2(xx_A - yy_A) = l_3^2 - l_2^2, \tag{3}$$

$$2(xx_C - yy_C) + 2(yy_A - xx_A) = C^2, \tag{4}$$

where $C^2 = l_3^2 - l_2^2 - l_4^2 + l_5^2$.

Equation (3) contains parameter φ_2, only, while equation (4) – parameter φ_5. The system is nonlinear but it can be reduced to quadratic equations

$$s\varphi_3 = (y - l_2 s\varphi_2)/l_3, \tag{5}$$

$$s\varphi_4 = (y - l_5 s\varphi_5)/l_4, \tag{6}$$

and they are used to calculate angles φ_3 and φ_4. The positional IPK is solved via those relations.

We consider a numerical example using equations for solving the IPK of a macro-mechantronic system. The following parameters are used as initial data for the structure shown in Fig. 2:

$$l_1 = 20mm; l_2 \equiv l_5 = 30mm; l_3 \equiv l_4 = 50mm \quad \varphi_2 = 140^\circ; \varphi_3 = 50^\circ; \varphi_4 = 130^\circ; \varphi_5 = 40^\circ. \tag{7}$$

Considering an absolute coordinate system XYZ (Fig.2), we find the following angles corresponding to the specified coordinates (20 and 65) of point B along axes X and Y:

$$\varphi_2 = 115^\circ,\ \varphi_3 = 49^\circ,\ \varphi_4 = 116^\circ,\ \varphi_5 = 42^\circ. \tag{8}$$

We also find the angular displacements for a forgiven initial state in the joints

$$\Delta\varphi_2 = 25^\circ, \Delta\varphi_3 = 1^\circ, \Delta\varphi_4 = 14^\circ, \varphi_5 = 2^\circ. \tag{9}$$

3. AN INVERSE PROBLEM OF THE KINEMATICS OF A MICRO- MECHATRONIC SYSTEM

Using the actuators, we should attain a position with coordinates $x + \Delta x$ and $y + \Delta y$, i.e. we should realize additional delta-displacement. Hence, $\Delta x = a$ and $\Delta y = b$ are known. We look for values of λ_j, i = 2, 3, 4 and 5, which would realize the position specified. However, we can solve the problem using one, two etc. operating actuators. For small values of λ in the DPK we derive the following equations

$$a = \sum_2^5 \lambda_j i_{jx}, \tag{10}$$

$$b = \sum_2^5 \lambda_j i_{jy}, \tag{11}$$

where

$$\begin{aligned} i_{2x} &= c\varphi_2 - s\varphi_3 c(\varphi_4 - \varphi_2)/s(\varphi_3 - \varphi_4) \\ i_{3x} &= c\varphi_3 - s\varphi_3 / tg(\varphi_3 - \varphi_4) \\ i_{4x} &= s\varphi_3 / s(\varphi_3 - \varphi_4) \\ i_{5x} &= s\varphi_3 c(\varphi_4 - \varphi_5)/s(\varphi_3 - \varphi_4) \end{aligned} \tag{12}$$

$$\begin{aligned} i_{2y} &= s\varphi_2 + c\varphi_3 c(\varphi_4 - \varphi_2)/s(\varphi_3 - \varphi_4) \\ i_{3y} &= s\varphi_3 + c\varphi_3 / tg(\varphi_3 - \varphi_4) \\ i_{4y} &= -c\varphi_3 / s(\varphi_3 - \varphi_4) \\ i_{5y} &= -c\varphi_3 c(\varphi_4 - \varphi_5)/s(\varphi_3 - \varphi_4) \end{aligned} \tag{13}$$

Obviously, the system is redundant – there are two extra DoF. Moreover, due to the closed kinematical chain, an area where point B can be positioned is bounded by each of the actuators. Areas of autonomous operation of actuators 3, 4 and 5 are outlined in Fig. 2.

The strategy of control of micro motions is based on the analysis of the capabilities of each actuator and on the capabilities of each couple and triad of actuators, namely 2 and 3, 2 and 4, 2 and 5, 3 and 4, 3 and 5, 4 and 5, 3, 4 and 5 etc.

Examine the operation of actuators 3, 4 and 5. Angles φ_2 and φ_5 are constants. The change of link length affects the change of angles φ_3 and φ_4, and it is found via the following equalities.

$$\Delta\varphi_3 = (c_x c\varphi_4 + c_y s\varphi_4)/l_3 s(\varphi_4 - \varphi_3), \tag{14}$$

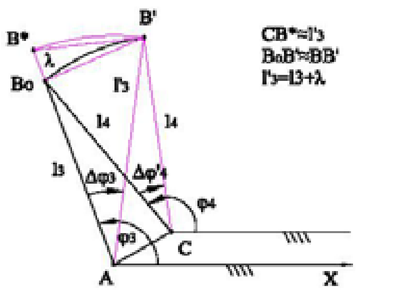

Fig. 2. Operational area of actuators 3, 4 and 5.

$$\Delta\varphi_4 = (c_x c\varphi_3 + c_y s\varphi_3)/l_4 s(\varphi_4 - \varphi_3)\,, \qquad (15)$$

where

$$\begin{aligned} c_x &= -\lambda_2 c\varphi_2 - \lambda_3 c\varphi_3 + \lambda_5 c\varphi_5 + \lambda_4 c\varphi_4 \\ c_y &= -\lambda_2 s\varphi_2 - \lambda_3 s\varphi_3 + \lambda_5 s\varphi_5 + \lambda_4 s\varphi_4 . \end{aligned} \qquad (16)$$

If actuator 3 is activated, only, it follows from (14) that

$$\Delta\varphi_3 = -\lambda_3 / l_3 tg(\varphi_4 - \varphi_3)\,,\ \lambda_3 \neq 0\,. \qquad (17)$$

The change of φ_3 yields a change of φ_4–$\Delta\varphi_4{}'$, which is found via the condition of existence of a kinematical chain (Fig. 3), namely:

$$c\Delta\varphi_4' = (l_3'^2 + l_4^2 - 4l_3'^2 s^2\frac{\Delta\varphi_3}{2})/2l_3'l_4\,. \qquad (18)$$

The results are similar if actuator λ_4 is activated, only.Then, the following relations are found

$$\Delta\varphi_4 = -\lambda_3 / l_3 tg(\varphi_4 - \varphi_3)\,, \qquad (19)$$

$$c\Delta\varphi_3' = (l_3^2 + l_4'^2 - 4l_4'^2 s^2\frac{\Delta\varphi_4}{2})/2l_3l_4'\,,\ \lambda_4 \neq 0\,. \quad (20)$$

It is seen from (17) and (19) that the variations of angles φ_3 and φ_4 are opposite to one another, i.e. if one angle increases the other one decreases. Thus, a total unidirectional effect is not to be sought. When activating the actuator of link 5, the variation of the two angles takes the form

$$\Delta\varphi_3 = \lambda_5 c(\varphi_4 - \varphi_5)/l_3 s(\varphi_4 - \varphi_3)\,,\ \lambda_5 \neq 0\,, \quad (21)$$

$$\Delta\varphi_4 = \lambda_5 c(\varphi_5 - \varphi_3)/l_4 s(\varphi_4 - \varphi_3)\,,\ \lambda_5 \neq 0\,. \quad (22)$$

Hence, we can look here for total effects being unidirectional with the effects of the other two actuators.

Note that when a single actuator is operating, the solutions are sought along boundary circle arcs or along concentric arcs plotted for different values of λ_j . If there are two operating actuators, all points in the outlined areas are possible solutions. This fact is shown in Fig. 3.

A most general solution of IPK can be found via the system of equations (7) and (8) completed by equalities

$$\operatorname{sgn}\dot\varphi_3 = \operatorname{sgn}\Delta\varphi_3\,, \qquad (23)$$

$$\operatorname{sgn}\dot\varphi_4 = \operatorname{sgn}\Delta\varphi_4\,. \qquad (24)$$

which guarantee elimination of the unidirectional looseness of the mechanical system. Velocities of links 2 and 5 of a macro MS are specified or found using the velocity of point B, while those of links 3 and 4 – by differentiation of the equations of the vector contour of the kinematical chain. The following relations are found in this case

$$\dot\varphi_2 = \left[l_2(\dot x c\varphi_2 + \dot y s\varphi_2) - (x\dot x + y\dot y)\right]/l_2(xs\varphi_2 - yc\varphi_2)\,, \quad (25)$$

$$\dot\varphi_5 = \begin{bmatrix} l_2(yc\varphi_2 + xs\varphi_2)\dot\varphi_2 + l_2(\dot y s\varphi_2 - \dot x c\varphi_2) + \\ + l_5(\dot x c\varphi_2 - \dot y s\varphi_5)/l_5(xs\varphi_5 + yc\varphi_5) \end{bmatrix}, \quad (26)$$

where

$$\begin{aligned} \dot\varphi_3 &= D_3 / D\,, \\ \dot\varphi_4 &= D_4 / D\,. \end{aligned} \qquad (27)$$

$$\begin{aligned} D &= l_3 l_4 s(\varphi_3 - \varphi_4), \\ D_3 &= l_4(l_5\dot\varphi_5 s(\varphi_5 - \varphi_4) + l_2\dot\varphi_2 s(\varphi_4 - \varphi_2)), \\ D_4 &= l_3(l_5\dot\varphi_5 s(\varphi_5 - \varphi_3) + l_2\dot\varphi_2 s(\varphi_3 - \varphi_2)). \end{aligned} \qquad (28)$$

4. MODELING AND SIMULATION OF A ROBOTIZED SYSTEM EMPLOYED TO INSPECT LASER CHIPS

The kinematical chain is shown in Fig. 4. Here, the working instrument (11) is a mechanical/vacuum gripper and it is oriented along axis Z. The rough positioning of the gripper is realized via a mechanisms with close KC consisting of 5 rotational couples (R1) with one degree of freedom, and two of them are active (located at the basis (o)) while the other ones are passive. The axes of rotation of all passive couples are parallel to axis Z. The positioning of the 5-link mechanism with respect to axis Z is realized by means of a rotational couple (T1) with one degree of freedom, which is located at the basis (O). Thus, the working plane is translated along axis Z and the mechatronic system becomes complete in space.

Each active kinematic pair forms one driving chain, i.e.: the first driving chain consists of bodies 2, 4, 6, 8 and the second driving chain consists of bodies 1, 3, 5, 7. The two chains are closed by a passive rotational couple (R1) between bodies 7 and 8. To meet the requirements of the inspection of laser chips, which is a micro/nano manipulation process, an additional degree of freedom (r1) is integrated between bodies 9 and 10 admitting grip rotation around axis Z.

To realize a finishing fine positioning and orientation of the working instrument, 4 piezo actuators are integrated in the driving chains. They realize translation in

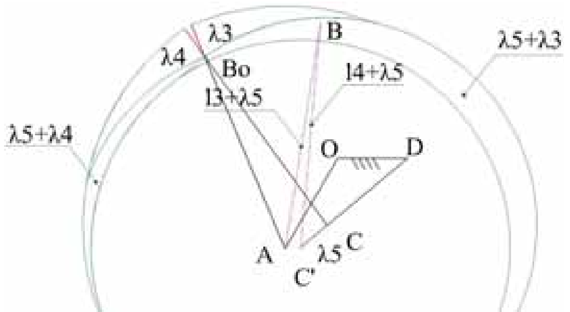

Fig. 3. Working area of a 5-link mechanism with two operating actuators.

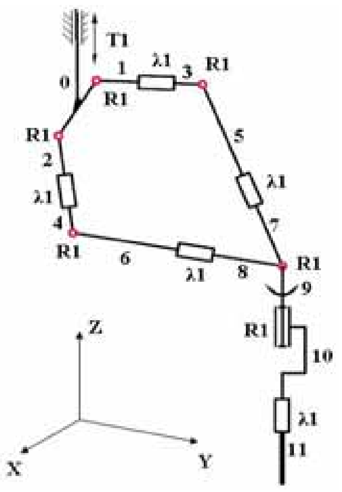

Fig. 4. a kinematical chain of a robot for visual inspection of laser chips. R1-rotation joint of a macro robot; T1 – translation joint of a macro robot; λ1 – translation joint of a micro robot.

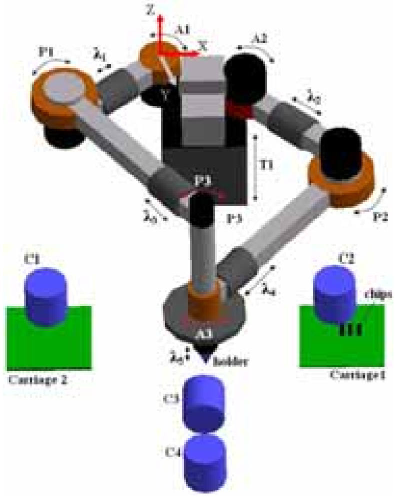

Fig. 5. A virtual model of a robotized system for visual inspection of laser chips.

the micro and nano range. An additional piezo actuator is integrated between bodies 10 and 11 performing fine translation along axis Z.

The degrees of freedom of the close kinematical chain are calculated by the formula

$$h = 3(n-1) - 2p_5 - p_4, \tag{29}$$

where n is the number of moving links and $p4$ and $p5$ are kinematic pair with 2 and 1 DoF;

Note here that $n = 9$, $p_4 = 0$; $p_5 = 9$, therefore $h = 6$. The DoF of whole robotized system are $h^* = 9$.

A virtual model of a robot (Fig. 5) is designed to validate the theory. The robot executes "grip-postion" operations. It is used for visual inspection of laser chips, where chips with dimensions up to 0.3 μm × 0.3 μm × 0.2 μm are scattered on Carriage 1. The operator grips a chip and inspects each of its 6 sides via a specific system of digital cameras or microscopes ($C1$–$C4$). Each laser chip should be specifically oriented in order to increase procedure accuracy. After inspection, chips are sorted in Carriage 2 for subsequent micro and nano operations. The whole procedure at this stage is executed by a man-operator. The problem is how to robotize the process, increasing some parameters such as accuracy and speed. A module strategy is used combining two devices – a macro robot with an operational range in centimeters and a micro manipulator with a working area in the micro working space.

The macro robot has 3 DoF and consists of a translation module ($T1$) and a carrying mechanism with 2 DoF ($A1$, $A2$). Each of the two driving chains has an active joint (a step motor) and a passive joint (hinge – $P1$, $P2$).

The kinematical chain proposed is closed by a passive joint (hinge – $P3$) thus forming a parallel structure. A rotational module ($A3$) is used for orientation of the working instrument performing rotation about the axis of the instrument, which is perpendicular to the working surface. The macro robot performs rough shift of the working instrument covering the respective macro working space.

The micro manipulator has 5 DoF (λ1–λ4) and a multilayered piezo motor is integrated in each arm of the driving chains. Note that the piezo motor performs translation in the micro range, with a resolution of up to 10nm. An additional piezo actuator (λ5) is fixed to the rotational module and it orients the working instrument, which can be a mechanical/vacuum gripper. The micro manipulator is used for fine positioning and orientation of the working instrument in micro and nano working spaces.

The virtual model of the robotized system for the inspection of laser chips is designed using the software package Solid Dynamics 2004+ (SDS2004+). To solve the inverse problem of kinematics we model a joint with three degrees of freedom (2 translations along axes X, Y and 1 rotation about axis Y) located between the active joint $A1$ and the passive one of the 5-link mechanisms that closes the system. Joint motion law along axes X and Y is provided and after executing the simulations in the SDS2004+ environment, we graphically derive the relative displacements of the angles of the 5-link mechanism sought. Considering the initial conditions (7) we obtain the following plots (Figs. 6, 7, 8 and 9).

Several advantages and disadvantages of the robotized system discussed can be outlined. Using the 5-link mechanism, the system becomes more stable due to its parallel structure and its precision of positioning and orientation increases. The system overall dimensions are reduced, thus covering a larger area of the working space. The disadvantage of the system are due to the more complex control needed and the necessity of entire fabrication of the active and passive joints.

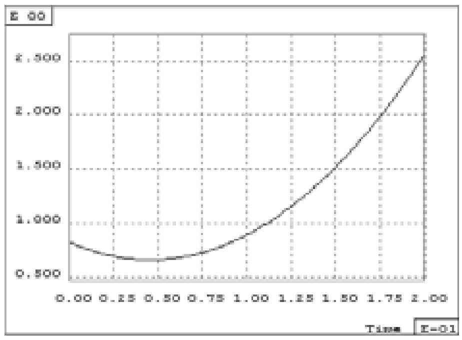

Fig. 6. Graphical presentation of the relative displacements of the angle sought: $\Delta\varphi_5 = 2.5°$

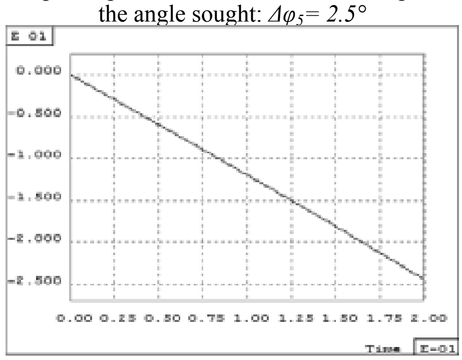

Fig. 7. Graphical presentation of the relative displacements of the angle sought: $\Delta\varphi_2 = -25°$.

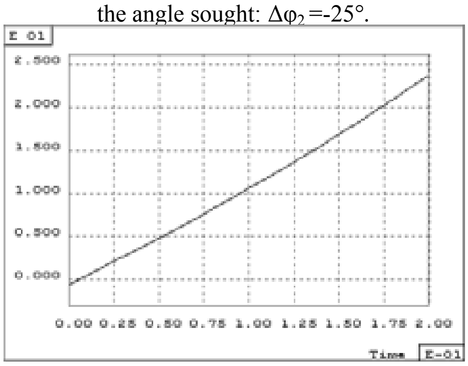

Fig. 8. Graphical presentation of the relative displacements of the angle sought: $\Delta\varphi_3 = 24°$.

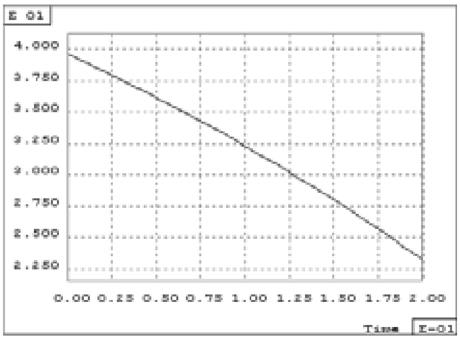

Fig. 9. Graphical presentation of the relative displacements of the angles sought: $\Delta\varphi_3 = -17°$.

5. CONCLUSIONS

A 5-link kinematical chain is synthesized and integrated into a robotized system for manipulation performance in micro and nano ranges and in particular – for inspection of laser chips. The inverse problem of kinematics is solved on micro and macro level and a numerical example is presented. A specific robot is modeled using a module principle. The robot consists of a macro robot and micro manipulator to meet the requirements of laser chip inspection. The theoretical set up is validated by the simulations performed using the software package SDS2004+. Further steps of the study are planned – synthesis of an approach for real development of a physical prototype and choice of appropriate actuating modules and control. The experimental results will be presented later.

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