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ADAPTIVE ROBOTIC SYSTEM FOR PRECIZE ASSEMBLY OPERATIONS

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Abstract
This paper presents new aspects of robotic adaptive system for precise assembly of prismatic, conical and rotational details and joints, modelling and 3D simulation of the system. Numerical solutions are discussed and some problems of so called smart assembly operations and mechatronic devices are described and solved.
Key words: robotic systems, adaptive assembly, simulation, 3D modelling

1. INTRODUCTION

The research interest of robotization of assembly tasks is to increase productivity and to reduce unit cost. One of the effective solutions of this problem is to increase the insertion speed of the robot which is very delicate in precision assembly. The greatest difficulty for robotic systems is the assembly of low clearance parts because the assembly clearance is smaller than the positioning errors of assembly systems. [1,2,3,4,5,6,7]

In general the process of adaptive assembly is a discrete state consisting of several phases demanding appropriate control through internal and external sensors. As a whole the process of assembly must be safe, fast and stable in time. According to the specifics of assembly tasks and operations the whole process can be divided to three phases: transporting movement with velocity, micro motions with low velocity and mating of details with author’s method of local dynamic compliance - $g_i(t)$.

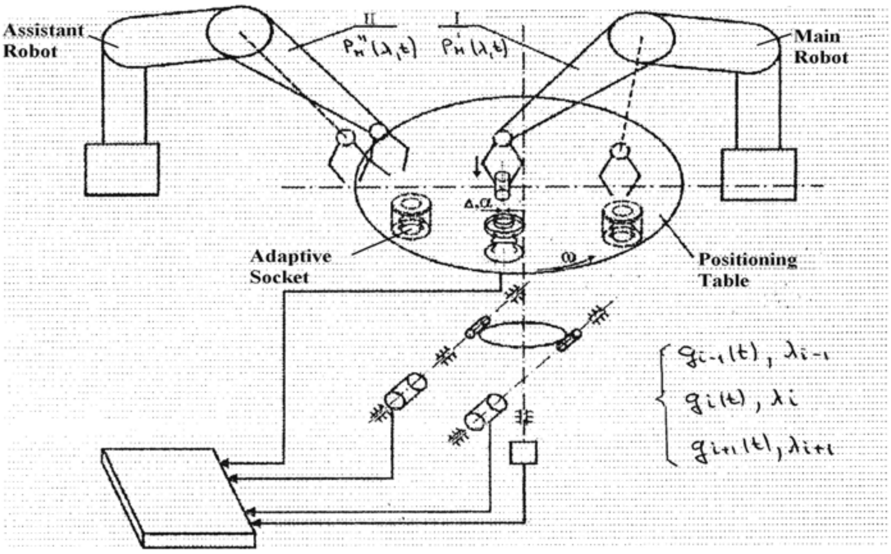

Fig.1. Two-robot assembly system with adaptive sockets

The aim of this paper is to suggest a methodology for creation and investigation of adaptive assembly system of rotational and prismatic details, without chamfers, based on using of new innovative solutions and complex simulations of robotic assembly system.

2. STRUCTURE OF ADAPTIVE SYSTEM FOR PRECIZE ASSEMBLY OPERATIONS

Lack of robot accuracy is caused primarily by unmeasured deflection of the robot structures or drives and low actuator/servo resolution. Interaction with the environment is hampered by the inability to accurately modulate the end-point impedance of the robots. The correction of small end point errors generally requires movement of several, if not all of the manipulators actuators. Parallel we have to monitor the relative positioning of two (or more) work pieces with generally high accuracy constraints to prevent the parts from wedging or jamming.

The goal of this study is to assess some alternatives from the viewpoints of generality, speed, complexity and industrial applicability including the case of non-rotational details with very small clearances.

The developed system, shown on figure 1, used for adaptive assembly or rotary and non-rotary details incorporates the advantages or 3R assembly robots (main and assistant) and a positioning robot (table) with adaptive assembly sockets (3 sockets for example) incorporating dynamic compliance and controlled seeking local micromotion.

From both scientific and practical point of view, robotized assembly of non-rotational details remains extremely difficult task characterized by:

a) High level of uncertainty of contact situations between the assembled details, having in mind that using three dimensional mesh for positioning and orientation, the possible contact situations are 1060. Even if ideal conditions and sensors are given there exist great difficulties determining the contact situations and the corresponding point of static balance.
b) The identification of orientation parameters for details of prismatic type (rectangular, quadratic etc. cross sections) is extremely difficult process often leading to insolubility.

The author's concept for local micro motion (using dynamic compliance of adaptive sockets) essentially improves the parameters of the robotized assembly system incorporating simplified and low-cost control system through industrial PD controllers.

The dynamic compliance concept used in the research, consists of:

a) Self-adjusting (self-correcting) function of the adaptive sockets, using level feedback through sensor blocks, self-correction of frequency micro motion (oscillations) and assembling force of the robot.
b) The formulated equations for dynamic compliance are the basis for planning of system of micro motions "offline" and designing a method and a strategy for adaptive robotized assembly.

The aim is to achieve efficiency of the technological macro movements as well as high speed, productivity and energy efficiency. The results from this research are very important when designing complex methodology for realization of robotic systems and creating new strategies for adaptive assembly of complex non-rotary mates without chamfers.

3. DYNAMIC MODELING AND 3D SIMULATIONS OF THE SYSTEM

The object of interest is a generalized structure (R⊥R||R) of an antropomorphic industrial robot with three degrees of freedom (three regional macro motions) and corresponding generalized coordinates: $q_1 = \varphi_1; q_2 = \varphi_2; q_3 = \varphi_3$, assuming that the links are rigid bodies and the joints are frictionless and non-compliant.

a) The dimensions of the links are given in advance (lengths $l_i; i = 1,2,3$) and their mass $m_i; i = 1,2,3$ are computable as well as the corresponding axial and centroidal moments of inertia from the individual tensors of inertia $J_{s_k}^{(i)}$.

b) Link 1 rotates with $\dot{q}_1$, link 2 realizes spherical motion with angular velocity $\dot{q}_2 = \dot{q}_1\overline{k}_1 + \dot{q}_2\overline{k_2}$; link 3 does a complex movement represented by a translation along with the centroid and a spherical movement around it: $\dot{q}_3 = \dot{q}_1\overline{k_1} + (\dot{q}_2 + \dot{q}_3)\overline{k_3}$.

Using Lagrangian dynamics together with method of divorced homogenous transformation[1,2] we can derive the dynamic equations of assembly robots with joints, which have n freedom and n+1 links, as follows:

$$\sum_{j=1}^{n} A_{ij}(q)\ddot{q}_j + \sum_{1}^{n}\sum_{1}^{n} B_{kj}(q)\dot{q}_k\dot{q}_j + h_i(q) = T_i, i = 1 \div n \quad (1)$$

where:

q_l - the joint variables;

$\dot{q}_j$ - the joint velocities;

$\ddot{q}_j, \ddot{q}_k$ - the acceleration of the joint variables;

$A_{ij}(q)$ – inertial coefficients;

B_{kj} – centrifugal and Coriolis coefficients;

h_l - gravity component; T_l - driving torques and forces;

The full dynamic model is presented in [2] and in this paper we shortly note that, the models derived, based on the Lagrange's equations have the advantage that they are in closed form concerning the geometrical, inertial and functional parameters of the mechanical system. The joint reactions are excluded and considering the immense computational power of today's computers one can successfully explore various aspects of the dynamic modelling of the robotized system.

This enables us to carry out dynamic synthesis of the macromovements (phase 1 and 2) and to build a strategy for dynamic behaviour. Based on the derived equations we can compute the appropriate joint torque of the regional structure of the assembly robot, considering the predefined generalized coordinates $q_i = q_i(t)$ and the finite increments of the generalized coordinates $o_i = |q(t_i) - q(t_i - 1)|$, in order to minimize to total system energy and power consumption..

Using MATLAB and Solid Works/Cosmos motion environments [8,9], we can derive effective 3D solutions for the corresponding parameters m_i, l_i, h_i, J_{sk}^i as well as get results applicable in the practice in order to achieve higher velocities and minimal duration of the transportation of details .

The developed software allows the user to learn about the robot, test programming concepts and visually present current or planned robot applications. These capabilities can reduce the time and cost associated with robot insallation and improves operation speed. The dynamic display of tool tip coordinates, joint angles, motor pulses and pose are fully consistent with those of a real robot doing the same motions. Then is possible to teach locations with the simulated virtual robot, or retrieve them from a file and then move through them.

The main conclusions from the numerical research are: (initial values of the lengths of links are: 0,6- 0,55 m for L1 and L2, and mass 3,60 and 1,58 kg respectively).

a) The time for actuating and braking of joint motors can be reduced twice or more (from 0.23s to 0.1s) given maximum angular velocity.
b) There exists a reserve for increasing the manipulated payload (end effector + detail) over two times (from 5kg to 12kg).
c) Given a discrete dynamic model and reduced mass of the end effector to 5kg, the length of the links of the assembly robot (link 2 and 3), can be increased with 0.25m to increase the operational space and to guarantee access to all peripheral devices of the robotized system.
d) The reviewed conclusions and the real constraints in choosing drive ratios (depending on the limited drive torque or velocity) are essential in the realization of new more efficient technological solutions, speed and productivity of assembly operations.

Using the original author's idea of designing the system from modular structures with 3R active joints and adaptive sockets (accommodating the concept of local dynamic compliance), we are able to combine higher speed, thus obtaining solutions to the extremely difficult assembly tasks of prismatic details without chamfers , avoiding wedging and jamming .

After the virtual 3D model is built, it is possible to conduct various simulations. This enables us to research the model, carry out different scenarios to see what will be the behaviour of the real adaptive assembly cell, using tools of visualization. The results from the kinematic simulations are presented further in the paper. (Fig.2 and Fig. 3)

The next goal is to simulate and optimize the structural parameters (lengths of links) and the control gains in parallel computing algorithms. Consider point-to-point motions in 2R planar case and assume the links are made of 4 mm – thick aluminium tubes, the actuated joint torques T1= 28 N.m, T2=16 N.m. A direct optimization routine procedure, based on gradient method is used to solve the optimization problems. As optimizing criteria we consider minimal position/velocity error, combined with maximal transportation speed of robotic arm.

The optimization procedure is in terms of a total of ten design variables, i.e two link lengths, two-link cross-sectional radii, two trajectory parameters and 4 control gains. The optimization steps and iterations are started with the initial values of:

L1 = L2=0.65 m, r1 =r2= 0,04 m, Cp1 = 50, Cp2 = 200, Cd1= 300, Cd2 =800.

Initial gains are obtained by tuning the controller to minimize the position and velocity errors at different assembly positions of technological environment. By expanding the sine and cosine functions of the joint coordinates, and substituting the joint motions and their velocities and acceleration into resulting equations, the inverse dynamic model is obtained as follow

$$Ti = Boj + \Sigma[Bi \cos(\omega t) + Bk \sin(wt)] , \qquad (2)$$

where Bi, k are constants for each particular motion in terms of the trajectory parameters, at respective values of joint coordinates, based on the mathematical model:

$$Qi = Aoi + \Sigma\{Ai \cos(wt) + Ak \sin (wt)\} \qquad (3),$$

and the respective parameters are: Qi - the i joint coordinates, Wi- the circular frequency, Ai – the trajectory coefficients ;

4. PRINCIPLES OF OPERATION OF ADAPTIVE ASSEMBLY DEVICES (SOCKETS)

The main manipulator must pick the assembled details from the peripheral devices, transport and position them to the corresponding assembly position for joining with base details. Usually the manipulator works in spatial or planar coordinates and is of anthropomorphous type.

The control system of the assistant manipulator consists of a circuit for positioning of the operational table and a circuit for coordination and orientation of assembly details. The base detail, fixed in the adaptive assembly device is positioned using precise kinematical motion in the active assembly area of the assistant manipulator's table. Even more, the positioning of the table is governed by the control system, which defines the driving signals for the corresponding motors. An incremental sensor realizes the positional feedback. The main robot for mating with the base detail feeds the manipulated detail. After that the locking mechanisms are released.

An adaptive assembly device using scanning vibration of the base details compensates the corresponding linear and angular inaccuracies. To achieve this double-sided shaft with the offset weights is actuated by the motor with angular velocity, determined by the control system and realized by the system for coordination and fixation. The platform of the adaptive assembly device oscillates depending on the setting of the dynamic system with controlled amplitude and frequency. The base detail oscillates too, thus realizing vibration motion and the corresponding seeking curves or surfaces with the other detail as well as compensating for the linear and angular three dimensional inaccuracies and accomplishing the assembly process.

By using of previous author's work [3], here in the case of assembly sockets, the mathematical model of the socket controlled micromotion is suggested in the form:

$$
\begin{aligned}
X(t) &= \frac{F(t)}{4K_x - M\omega^2}\sin \omega t \mp \frac{\mu\lambda t}{4K_x} \mp \frac{\mu G}{4K_x} \\
Y(t) &= \frac{F(t)}{4K_y - M\omega^2}\cos \omega t \mp \frac{\mu\lambda t}{4K_y} \mp \frac{\mu G}{4K_y} \\
\theta(t) &= \frac{H(t)}{4K_\theta - A\omega^2}\sin \omega t \mp \frac{\mu\lambda t R_T}{4K_\theta} \mp \frac{\mu G R_T}{4K_x} \\
\psi(t) &= \frac{H(t)}{4K_\psi - B\omega^2}\cos \omega t \mp \frac{\mu\lambda t R_T}{4K_\psi} \mp \frac{\mu G R_T}{4K_\psi}
\end{aligned} \tag{4}
$$

where:

$\underline{K}$ - elasticity matrix of the adaptive device with respectively scalar coefficients on the coordinates; (K_i)on x, y, z, θ, ψ, φ - linear and angular coordinates;

M – mass of dynamic system, *A,B* – main inertia moments of the adaptive device,

F (t) – amplitude of harmonic generating force

H (t) – amplitude of harmonic generating moment

ω - natural frequency

F_T - friction force between assembled details (see also formula (8) in [3])

λ - feedback parameter of the adaptive socket, describing threshold feedback,

G - weight of mechatronic adaptive module(socket)

μ - dry friction coefficient,

R_T - friction radius at contact interaction of assembled details

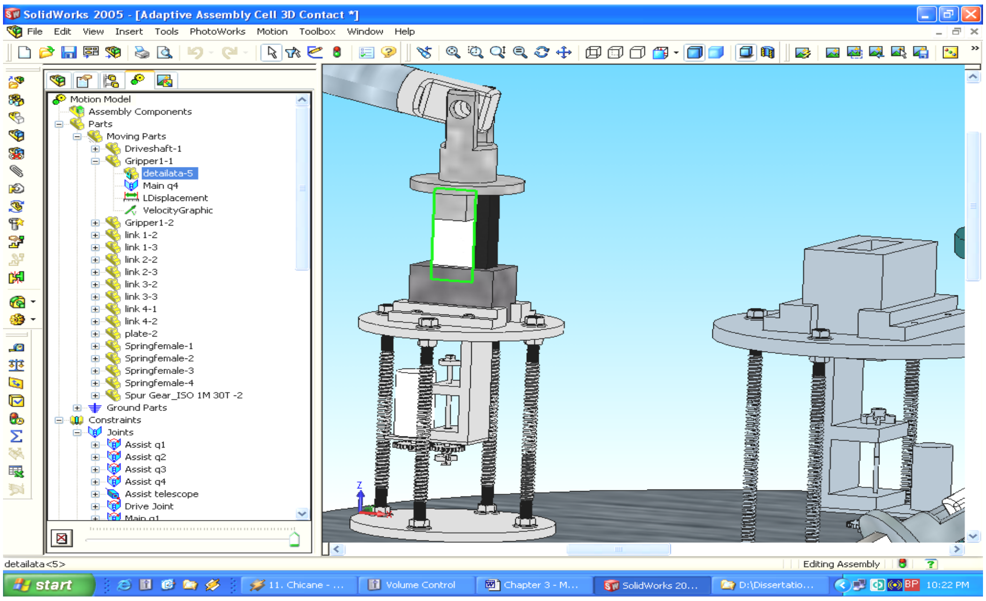

Fig.2. 3D dynamic simulations of robotic assembly process with adaptation

5. ADAPTIVE ASSEMBLY OF NONROTATIONAL (PRISMATIC) DETAILS - SMART SOLUTIONS

In the process of implementing this difficult task it is essentially to introduce additional sensors for the assembly process. We introduce two servo contours for measuring and control (I and II):

a. The gripper's force: $\tilde{F}_3(t)$ for the upper assembly detail using two tactile sensors and constant monitoring of its value under contact interaction of the assembled details. (tactile perception)

b. Measuring of the horizontal F_k^h and the vertical F_k^v components of the force acting on the base detail.

Using these two servo circuits we can achieve additional functionality of the robotized assembly cell for realizing difficult assembly operations and multi positional adaptive assembly incorporating various metrics and mass of the details.

The algorithms for adaptive assembly are represented by a system of calculations (5), until the generalized positional error is zero and the contact surfaces are mated.

$$\begin{cases} g_{i-1}(t), \lambda_{i-1}, P_{M_{i-1}} \\ g_i(t), \lambda_i, P_{M_i} \\ g_{i+1}(t), \lambda_{i+1}, P_{M_{i+1}} \end{cases} \qquad (5)$$

Where $$P_{M_i} = P_H + \lambda_I . t \qquad (6)$$

λ_i - feedback parameter

P_H - initial value of the assembly force

g_i - dynamic compliance of the local adaptive socket, calculating off-line and one-line controlled

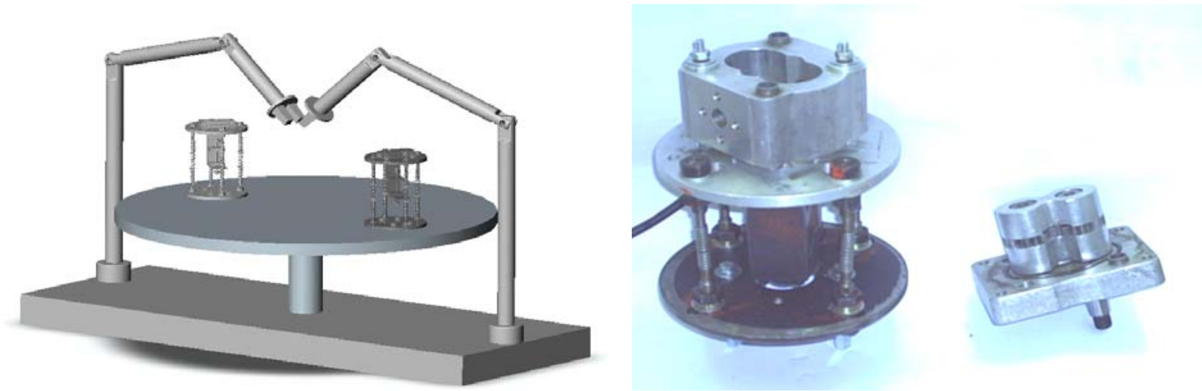

Fig.3. a) 3D model of adaptive system; (b) real prototype of an assembly socket

The three dimensional model of the device is built using Solid Works/Cosmos Motion 2005 environment assuming that all main dimensions of the real model are exactly reproduced. All kinematic connections and degrees of freedom are kept in accordance with the original, as well as all mass and inertia characteristics. The correct construction and mating of all the details in the assembly allows us to create a virtual assembled model of the adaptive assembly cell (fig.3 a). Further more the problem of straight line trajectory movement was solved and also exported. Using the mathematical results obtained the 3D model of the robot was driven to various location and its position and orientation was measured. The results coincided completely with the calculated ones. Further more a simulation of the adaptive assembly socket was conducted and the results again coincided completely with the experimental data obtained from a working real prototype (figure 3 b). Even more: a simulation of adaptive assembly operation was made and it also proved successful. Study of proposed models allows to understand the dynamic insertion mechanism and to find the conditions guarantying the success of this operation, reduction the friction forces (more than 2 times) and avoiding wedging and jamming in case of chamferless assembly.

The next step in the development is to calculate most precisely the drive parameters of feeding (positioning) table in order to simulate the whole adaptive assembly system in 3D aspect.

6. CALCULATIONS OF REQUIRED TORQUE NEEDED FOR DRIVING THE POSITIONING TABLE:

It is necessary to calculate precisely the table driving torque to obtain the most effective solutions. An acceleration torque, friction torque and load torque are available as the required torque.

$$T = T\alpha + T\mu + T_L \quad (7)$$

T: Required torque (N.m) Tα: Acceleration torque (N.m)

Tμ: Friction Torque (N.m) T_L: Load torque (N.m)

Acceleration torque (Tα):

The acceleration torque is obtained from the calculations of inertia of driving and load, multiplying with angular acceleration (wellknown equation)

Friction torque (Tμ):

The friction torque is obtained from the following equation:

$$T_\mu = \frac{\mu(9{,}8W_T + F_2).P}{2\pi.\eta} \times 10^{-3} \quad (8)$$

Tμ: Friction torque (N.m); μ: Friction coefficient

P: Ball screw lead (mm); WT: Movement weight (kg)

η: Ball screw efficiency; F2: Force vertically applied to table during movement (N)

Load torque:

The load torque is obtained from the following equation:

$$T_L = \frac{F_1.P \times 10^{-3}}{2\pi\eta} \quad (9)$$

TL: Load torque (N.m); P: Ball screw lead (mm), η: Ball screw efficiency,

F1: Force pushed against the travelling direction of table (N)

- Based on the systems of equations (1) – (9), a methodology for creation and investigation of such kind of mechatronic systems was developed for the purposes of practical implementation and new assembly technology.
- Real experiments on adaptive assembly operations – tests have been performed with workpieces (prismatical and axisymetrical) with clearance less than 0,014 mm and full insertion was possible up to linear errors of 0,7-0,9 mm and angular errors of about 2 ^{0}. The time of seeking and assembly is less than 1,8 sec. For 300 experiments there is not detected any wedging or jamming.

7. CONCLUSIONS

Fast changes of product development need designing of new assembly systems and adaptable robotic units. For small and media size enterprises the effective automation could be obtained using intelligent manufacturing (robotic) systems and modules. Applying dynamic and virtual simulation and control optimization we are able to obtain more effective solutions for know – how assembly technologies and high performance manufacturing systems.

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