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MODELLING AND SIMULATION ASSEMBLY TASKS USING ROBOT HANDS

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Abstract Assembly operations can be made using anthropomorphic robot hands, under active stiffness. Assembly task analysis can be made by studying the kinetostatic parameters measured during the process. In order to minimise the experiment costs and time, models are designed to simulate the process. As an application for the presented assembly study, a grooved bolt, had been chosen. This kind of task can be hardly fulfilled by robot hands, unless the active stiffness control is used. So, an assembly strategy had been made, using different stiffness for each step of the assembly operation, which provides a better centring of the shaft.

1.Compliant grasping model

As discussed in previous analyses, the external forces that appear in the assembly task provide the joint torque reaction that can relate by:

$$\overline{\Gamma_i} = K_{\theta_i} \cdot \delta\overline{\theta_i}\,, \tag{1}$$

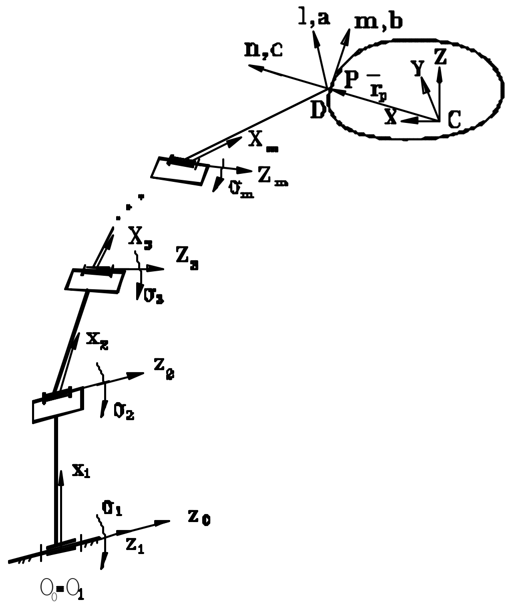


Fig. 1 Coordinate systems for a single finger touching a grasped object

where:

K_{θ_i} - the joint stiffness.

The *m* joints servos would produce an *mxm* joint stiffness matrix:

$$[K_\theta] = \begin{bmatrix} K_{\theta_1} & 0 & \dots & 0 \\ 0 & K_{\theta_2} & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & K_{\theta_m} \end{bmatrix} \tag{2}$$

Stiffness matrix $[K_\theta]$ of the hand presented in fig. 2 become:

$$[K_\theta] = \begin{bmatrix} [K_{\theta_1}] & 0 & 0 \\ 0 & [K_{\theta_2}] & 0 \\ 0 & 0 & [K_{\theta_3}] \end{bmatrix} \tag{3}$$

The joint compliance matrix is obtained by invert the joint stiffness matrix, $[K_\theta]$:

$$[C_\theta] = [K_\theta]^{-1} \tag{4}$$

where the product

$$^D[J(\overline{\theta})] \cdot [C_\theta] \cdot {}^D[J(\overline{\theta})] = {}^D[C_\theta] \tag{5}$$

represent the equivalent compliance matrix for the fingertips due to the servo compliance, expressed in the D(a,b,c) reference.

To the contollable joint compliances, the uncontollable structural compliance must be added.

The finger of the hand consists of 3 links. To computing the structural compliance of the finger, assume that we view each individual link as a cantilever beam. Referring to beam theory, we can find the compliance of a cantilever links in its local coordinates:

$$^{O_i}[C_{l_i}] = \begin{bmatrix} \frac{l_i}{EA} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{l_i^3}{3EI_z} & 0 & 0 & 0 & \frac{l_i^2}{3EI_z} \\ 0 & 0 & \frac{l_i^3}{3EI_y} & 0 & -\frac{l_i^2}{3EI_y} & 0 \\ 0 & 0 & 0 & \frac{l}{GI_p} & 0 & 0 \\ 0 & 0 & -\frac{l_i^2}{3EI_y} & 0 & \frac{l_i}{3EI_y} & 0 \\ 0 & \frac{l_i^2}{3EI_z} & 0 & 0 & 0 & \frac{l_i}{3EI_z} \end{bmatrix}; i = 1 \to 3 \quad \text{for each finger} \tag{6}$$

and in the D(a,b,c) reference by following equation:

$$^{D}[C_{l_i}] = {}^{D}_{O_1}[J_{l_i}] \cdot {}^{O_i}[C_{l_i}] \cdot {}^{D}_{O_i}[J_{l_i}]^T, \; i = 1 \to 3 \tag{7}$$

where ${}^{D}_{O_i}[J_{l_i}]$ represent the cartesian transformation matricea from $O_i(x_i, y_i, z_i)$ to D(a, b, c).
The structural compliance matrix for finger 1(similar for finger 2), is expressed by :

$$^{D}[C_{s_1}] = {}^{D}[C_{l_1}] + {}^{D}[C_{l_1}] + {}^{D}[C_{l_1}] \tag{8}$$

The concatenated structural compliances of the hand, in the fingertips coordinates becomes:

$$^{D}[C_s] = \begin{bmatrix} {}^{D}[C_{s_1}] & [0] \\ [0] & {}^{D}[C_{s_2}] \\ (6\times 6) & (6\times 6) \end{bmatrix} \tag{9}$$

The concatenated structural compliances of the hand, in the fingertips coordinates become:

$$^{D}[C_\theta] + {}^{D}[C_s] = {}^{D}[C] \tag{10}$$

If ${}^{D}[C]$ is invertible, which it usually will be if ${}^{D}[C_s]$ is not negligible, one can obtain the concatenated fingertip stiffness matrix ${}^{D}[K]$.

To impose a compliant feature of a grasp, it has to be established a stiffness matrix ${}^{C}[K]$, of the finger/object assembly, [1], which represented in P(l, m, n), reference that is conected to the object contact points, can be writen as :

$$^{C}[K] = {}^{P}_{C}[J]^T \cdot {}^{P}[K] \cdot {}^{P}_{C}[J] \tag{11}$$

The elastic behaviour of a grasp can be writen as :

$$^{C}\overline{F} = {}^{C}[K] \cdot \delta^{C}\overline{X} \tag{12}$$

For small displacements of the grasped object, expresed by the $\delta^{C}\overline{X}$ vector, the variation of contact forces, in P(l, m, n) reference, will be :

$$^{P}[\delta F] = {}^{P}[K] \cdot {}^{P}[\delta\overline{X}] = {}^{P}[K] \cdot {}^{P}_{C}[J] \cdot {}^{C}[K]^{-1} \cdot {}^{C}\overline{F} \qquad (13)$$

Relations (13), describe the variance of the contact forces as a function of the exterior forces, for a certain prescribed stifness $^{C}[K]$.

Variations of contact forces will lead to variations in motor torques, expressed by the column matrix $[\delta\Gamma] = [\delta\overline{\Gamma}_1, \delta\overline{\Gamma}_2, \delta\overline{\Gamma}_3]^T$:

$$[\delta\Gamma] = {}^{D}[J(\overline{\theta})]^{T} \cdot [H]^{T} \cdot [H]^{P} \cdot [\delta F] \qquad (14)$$

If the grasping forces are imposed $^{D}[F_0]$, than the resulting contact forces will be :

$$^{D}[F] = {}^{D}[F_0] + {}^{D}[\delta F] \qquad (15)$$

where $^{D}[F] = [{}^{D}\overline{F}_1, {}^{D}\overline{F}_2, {}^{D}\overline{F}_3]$, and the motor torques in the joints are expresed by the relation :

$$[\Gamma_C] = [\Gamma_0] + [\delta\Gamma] \qquad (16)$$

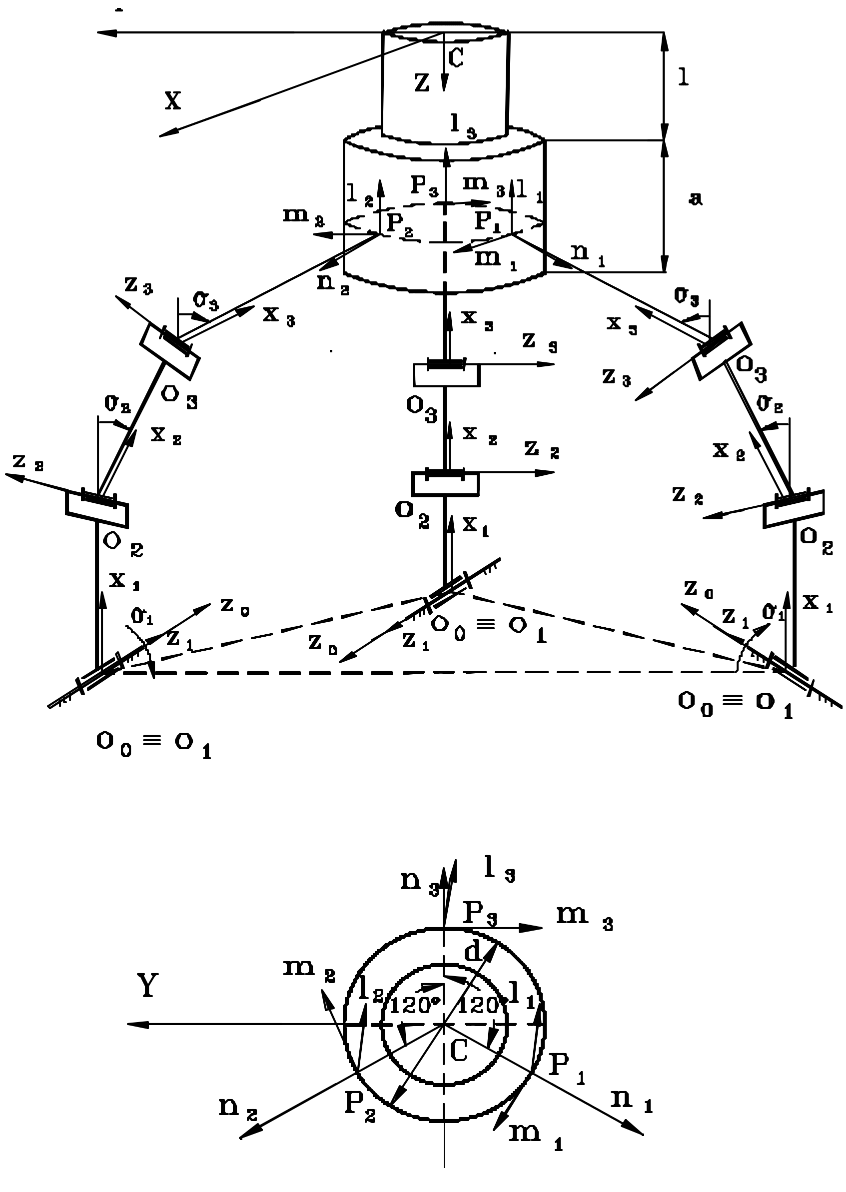


Fig. 2 Three finger grasping

In fig 3. the grasping stiffness control flowchart is presented according to the above-presented model, [1]. Initial values are realised by the signal generator and the "indeg" amplifier. The initial signal is transformed in torques, which together with the command angular displacements are passed to the fingers. The motors angular displacement response is sensed together with the perturbations and fed back to be summed with the command signal. The flowchart also contains a subsystem, which is able to modify the finger/object contact stiffness according to the applied assembly strategy.

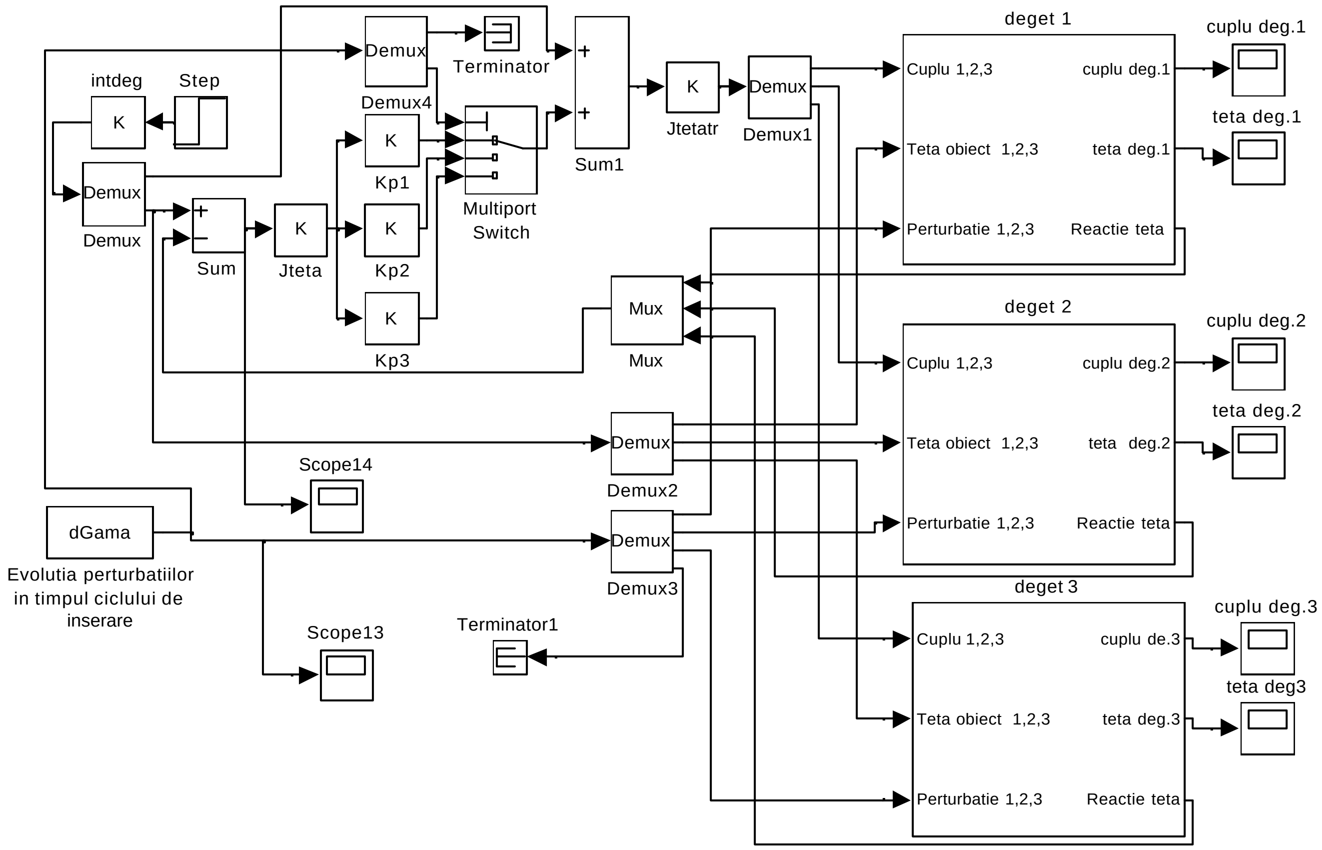


Fig. 3 Active stiffness control system flowchart, for three finger grasping.

2. Assembly strategy

As an application for the presented assembly study, a grooved bolt , had been chosen. This kind of task can be hardly fulfilled by robot hands, unless the active stiffness control is used. So, an assembly strategy had been made, using different stiffness for each step of the assembly operation, which provides a better centring of the shaft.

After positioning the bolt in the mechanical hand (fig.2), the robot arm is moved toward the surface containing the hole, until the contact is detected by the multicomponent force sensors, placed on each finger very close to the fingertip. It is assumed that the assembly task is fulfilled when the bolt center reaches the hole center. Due to positioning errors the exact match is very difficult. For this reason an assembly strategy has to be designed.

1)Under stiffness control the hand is moved toward the holed surface, along the Oy axes.

To ensure contact with the surface and provide penetration of the bolt in the hole, it is assumed that the bolt is pushed toward the surface with a normal force F_C. There are no position constrains along the direction Oy, so a greater stiffness will be considered along this axes. At the same time a small stiffness will be adopted after the third axes (Ox), to permit the bolt to center itself naturally in the hole. Applying the inverse calculus model of grasping stiffness presented in [1], the matrix ${}^{P}[K_1]$ had been determined.

2) If the centreing is not realised during the travel along (Oy) axes, the movement of the bolt will be continued after the (Ox) axes. This step requires a greater stifness on (Ox) and smaller on (Oy).

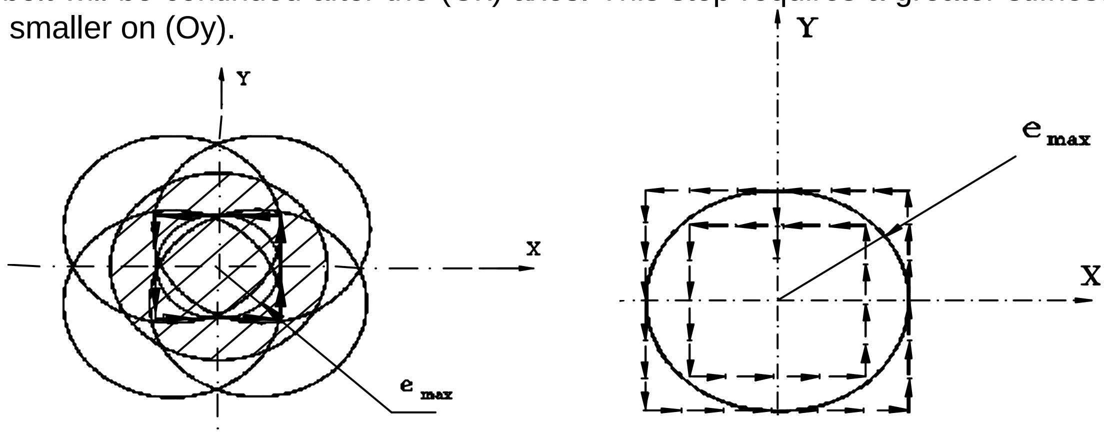


Fig.4 a) Positioning error. b) Bolt displacement on the holed surface

Within this strategy it is assumed that the bolt positions related to the holes position are inner to a circle of e_{max} radius – the maximal positioning error of the robot arm (fig.4.a). In fig. 4.b are presented the movements made along axes Oy and Ox in the first and second step. Movements are made folowing the edges of concentrical squares, untill the bolt is centered on the holes edge. During these steps the rotational stifnesses after Oy and Ox are set high in order to maintaine the orientation of the bolt. To establish whether the bolt had penetraited in the hole, the penetration depth is monitorised. If the penetration is not deep enough, the proces will be repeated untill the task is fullfiled.

3) To ensure that the bolt will not be stocked in an intermediate position during penetration, in this step all the stiffness will be maintained low. As a supplementary measure, the compliance centre C(x,y,z), specified by a diagonal matrix, will be placed on the tip of the bolt. Pushing the bolt in the hole with a F_c force after Oz direction will continue penetration. Simultaneously a rotation will be made around Oz. During this step the force, time and penetration depth will be sensed. If the required depth is reached the process is considered complete.

3. Assembly task modelling

Assembly task analysis can be made by studying the kinetostatic parameters measured during the process. In order to minimise the experiment costs and time, models are designed to simulate the process. So a set of experimental measurements are used to validate an MATLAB-SIMULINK model, which is used later to analyse the process.

Advanced programing methods allow us to use numerical modules to generate initial data for the model, in the design stage. Such module is used to simulate the evolution of forces during the assembly operation of a bolt penetrating a hole, when the task is performed by a robot hand with active control of the grasping stiffness.

3.1 Three fingered grasping model

Compliant grasping model, presented in [2], fig.3, includes a module that changes finger/object stiffness, by means of used penetration strategy.

Interaction between grasped object and the surface that contains the hole is described by the contact torsor : ${}^{C}\overline{F} = [0, -\mu F_C, F_C, 0,0,0]^T$ or ${}^{C}\overline{F} = [-\mu F_C, F_C, 0,0,0]^T$.

Test data are given to the model by “d Gama” block, representing the kinetostatic parameters values.

3.2 Environment modelling

Because the interaction of the grasped object with the environment is given by the normal force $\overline{F}_C$, the purpose of environment model is to establish the variation of this force during the movement of the bolt along the surface that contains the hole.

It is assumed that at holes edge, the variation of the contact force is elliptical along the radius direction of the hole. So according to fig. 5 results :

$$\begin{cases} \dfrac{y'^2}{a^2} + \dfrac{z^2}{b^2} = 1 \\ V = \sqrt{x^2 + y^2} \end{cases} \tag{17}$$

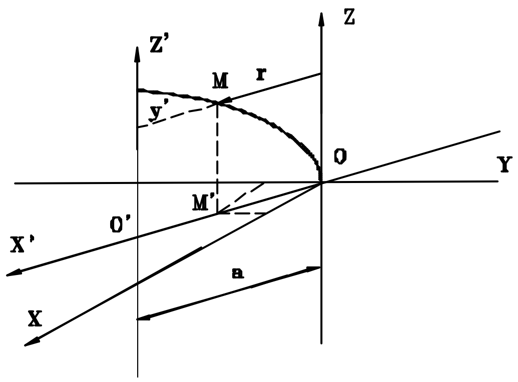


Fig.5 Environment modelling

where $Y' = a - r$, $a = D_a$ (hole’s diameter), $b = F_C$

$$\frac{(a-r)^2}{a^2} + \frac{z^2}{b^2} = 1 \quad sau \quad a^2 \cdot z^2 + (x^2 + y^2)b^2 - 2b^2 a\sqrt{x^2 - y^2} \tag{18}$$

From equation (18) results:

$$F_z = z = \frac{b}{a}\sqrt{x^2 + y^2} \cdot \sqrt{2a + \sqrt{x^2 + y^2}} \tag{19}$$

The variance of contact force on the surface containing the hole is given by :

$$F = f(x,y) = \begin{cases} F_C, & \text{if } x^2 + y^2 > a^2 \\ F_z, & \text{if } x^2 + y^2 = a^2,\ x^2 + y^2\ ?\ 0 \\ 0, & \text{if } x^2 + y^2 = 0 \end{cases} \tag{20}$$

3.3 Test data generation

The purpose of test data is to checkout the models behaviour under various conditions, which can overcome during penetration. Therefore a specific module had been designed to generate test data.

The module simulates the bolt’s movement along an imposed trajectory, which covers all possible positions of the hole. This movement is realised by iterating the position parameters along Ox and Oy directions, calculating the contact force at each iteration.

At start the iteration step is assumed to by high, until the bolt is reaching the hole’s edge. After this point the iteration step is set low to ensure better positioning precision. At every step the contact force is calculated and the bolt’s movement along the surface is continued, until the contact force will reach a minimal value. After that the bolt will be moved perpendicular to the previous direction, until a minimal contact force is obtained. If after this point the force increases again, the movement direction will be changed. When the hole centre is reached, the movement of the bolt will be changed along the Ox direction in order to penetrate the hole. If the bolt's groove position do not match the hole's groove position, the contact force will increase again and the program will simulate a rotation of the bolt around the Ox axes, until the contact force will be zero again. Reaching this point it is assumed that the penetration was complete. The values of dG are saved to be used by the simulation model presented in [2], also the module graphically represents the evolution of all calculated parameters d^DF.

<u>Model</u> Holes position : r=2, $\theta = \frac{p}{6}$

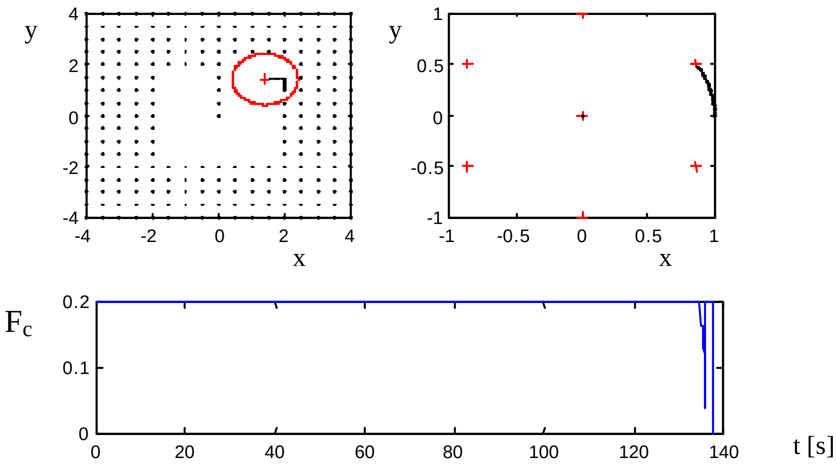


Fig.6 Trajectory of the bolt and contact force diagram

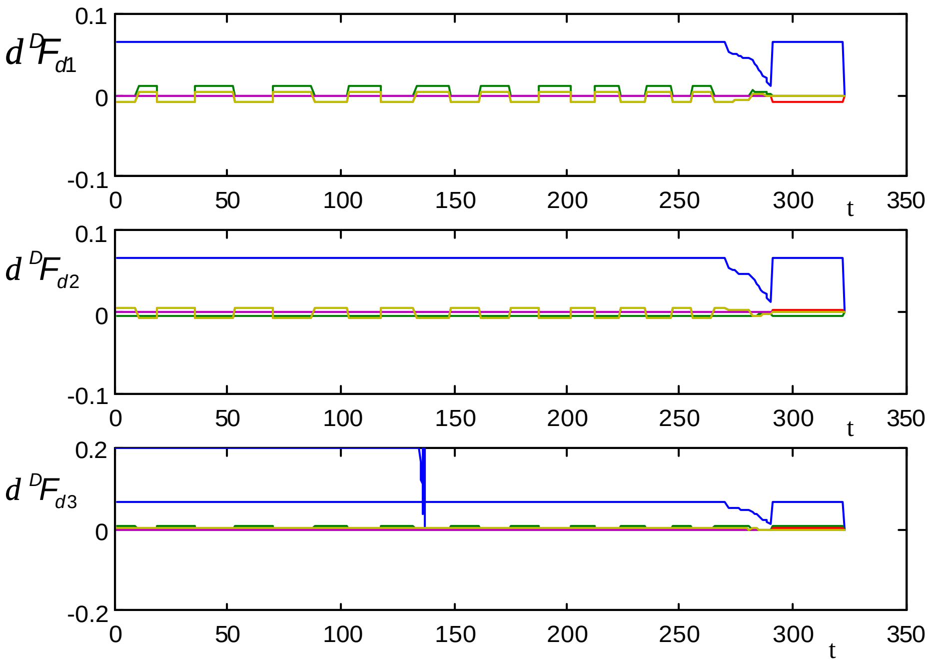


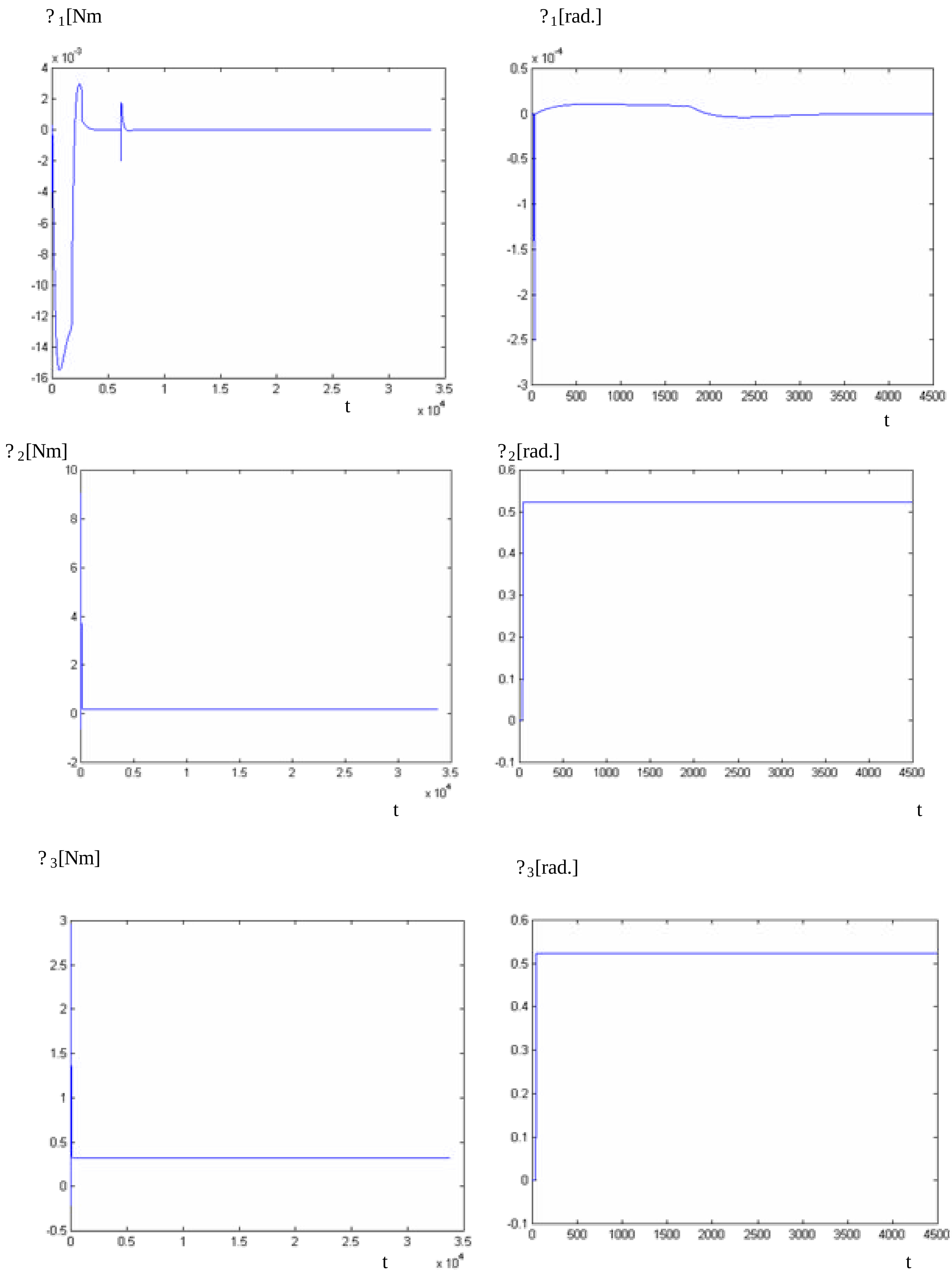
Fig.7 Grasping force variation

4. Simulation of assembly operation and simulation results

Simulation was made using the MATLAB SIMULINK environment.

Test data were obtained with "Strateg" module, and there are introduced in simulation by "dGama" block. During simulation the motor angular displacements and torques were watched over. There is also analysed the behaviour of the model in case of random perturbation. The results of simulation are presented next.

Fig.8 Motors couple and position angles for finger 1



4.Conclusions

The stiffness control approach to force control in an anthropomorphic hand has been shown to be a useful and effective means of effecting force control in assembly tasks. Stiffness control allows the programmer to think in terms of desired part trajectories during assembly.

Simulation of assembly tasks using anthropomorphic hands has evidential possibility change of stiffness grasp under program control to match varying task requirements. Simulation process continue two steps:

- test data generation
- simulation active stiffness control model

5. Bibliografy

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