A force control for a peg-hole system in assembly technology

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ABSTRACT

In this paper, the problem of a mated-piece inser- tion is examined due to the current search for precision in the process of fitting. When the required precision is so high that the machine vision is no longer useful, it is necessary to control the force, distinctively in the operations where the gap is narrow such as gear matching, machine tooling or special automation. Thinking about that objective, a peg-hole model was developed in Matlab based on both, the geometric deformation of the sensor, and another passive element for calculating the reaction forces, which are present in the mating process.

Once the peg-hole model is implemented, it is possible to develop a force control for the reference position of the robot's final point. The force control's goal is to lower/adequate the reaction forces and this ensures that the peg reduces the contact forces with the walls of the hole. This control calculates the new position of the robot, taking the old position and adding the reaction force multiplied by a proportional constant. The proportionality constants are tuned using an empirical knowledge of the system. At the end of the document the results from the simulation are shown and the tolerance between the piece and the hole is varied.

Keywords:

Fitting Assembly; Precise; Peg; Hole; Force Control; Assembly Simulation.

I. INTRODUCTION

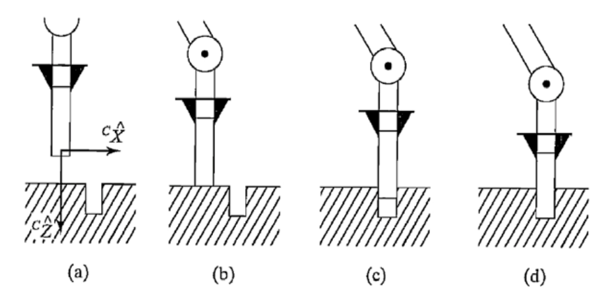
Nowadays, the importance of assembling applications and their requirements are increasing in industry. For example, these applications need to be more accurate, efficient, faster and safer. All of these must be improved for the sake of productivity and the quality of end products, especially in industries that perform gear matching, machine tooling, automation, or construction equipment manufacturing.

There are two ways to achieve a precise fitting assembly. The first way is performed using only a normal position control, which can be costly for specialized systems. However, with the use of force sensors the precision of fit is increased according to the position-force-control. Due to small variations in one relative position, a high contact force in the sensor is generated and with this data the positional accuracy is improved [1].

The second way consists of measuring the force for the assembly to reduce those costs, particularly where the contact between the robot and its environment occurs. This contact force influences the quality of performance, which does not only rely on the robot's trajectory as in the simple applications of welding or pick-and-place operations. If the contact force is too high, it may cause damage to the product or even injure personnel, which is an immeasurable loss. This can be avoided by knowing the assembly's environment and by using an appropriate force control.

The operation of fitting two parts occurs frequently and consists of two types of configurations. The first is a clearance fit design where the parts have space to move freely against each other, and the second is a press fit where the two parts are designed to be fixed to each other. In essence, both configurations have the same process. The only difference is that the assembly force must exceed the static friction force between two joined components. In assembly technology, the most common fitting process is fitting a shaft in a hole, which is guided by ANSI and ISO, with different tolerances for both components [2] [3]. Figure 1 shows the typical process.

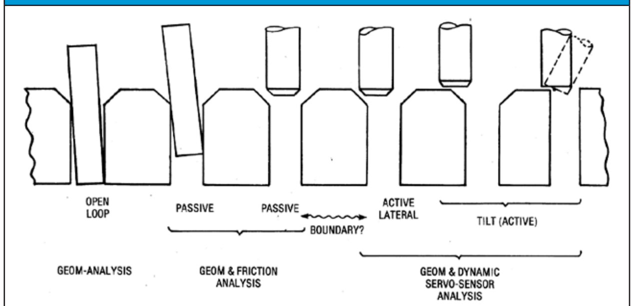
Fig. 1. Fitting process for shaft in a hole [4]



The easiest case for an assembling process is a system with a peg and hole geometry. In this system, a rigid peg is introduced into a rigid hole while the forces are measured by a force sensor, which is placed in the gripper of the assembling robot. With this model, it is possible to analyze all reaction forces between the piece and the environment and to generate a force control. There is a lot of literature about peg-hole systems that supports the research in this article [5].

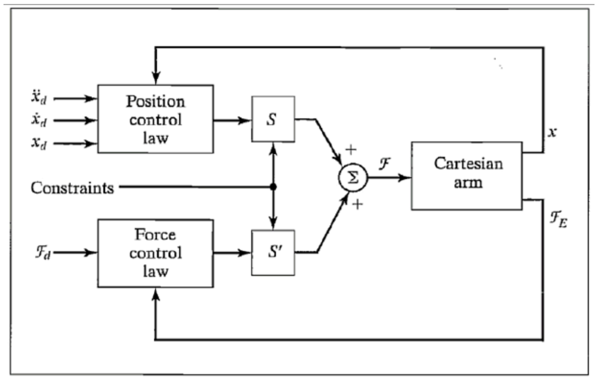
For the fitting control, there is also the possibility of using only a passive element in the form of springs to compensate error, but here the function is limited. When the hole does not have a chamfer the rod gets hung up on the corner, hence active control becomes necessary. For different contact cases of peg and hole, geometric and friction analysis must be supplemented by dynamic consideration of sensors and servomechanisms. (Figure 2 active system).

Fig. 2. Error regions and strategy options [6]



The two kinds of active strategies have been recognized. One is called "logic branching" and the other one "accommodation". Logic branching consists of enumerating the cases of relative position that could occur during the process and programming a sequence of test moves to determine which case is in effect [7]. With this strategy, a hybrid force/position controller is normally used (Figure 3), containing the sequence in the matrix *S*, which is changed by an external element, depending on the constraints of the states. This matrix *S* chooses between a force control and a position control, depending whether the piece is allowed to move in this direction or not [1].

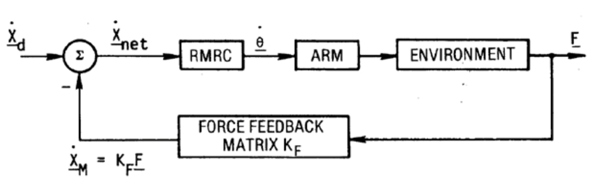
Fig. 4. Accommodation loop [6]



The accommodation strategy concept aims to use force torque data from the assembly action to control the fine motions (Figure 4). Detailed analysis of the force interactions between the parts is necessary so that the error conditions can be recognized directly.

This paper studies a precise fitting control, based on an accommodation strategy concept. For this a Matlab 2D model was developed, which allowed the use of the force torque data for the control without considering constraints or states.

Fig. 3. Hybrid force/position controller [1]



II. RELATED WORK

The peg-hole system is a process that belongs to the interests of several investigations. The first researcher that proposed the theory of the accommodation loop was Nevins in his paper "The force vector assembler" [8] [6]. The researchers used a control loop to insert a screw through a hole and later lock it with a nut. After this paper, the strategy control was developed [9] [10]. In this control, the user must decide the strategy of the insertion and define the constraints between them. This control is very stable, but the programmer has to be very aware and conscious of the movements before implementation.

The main purposes of this article are: Tuning the proportional values of the accommodation loop (apart from this implementation) and looking forward to develop a model of a peg hole system, which can be used for the performance of other kinds of controllers.

III. MODELING ENVIRONMENT

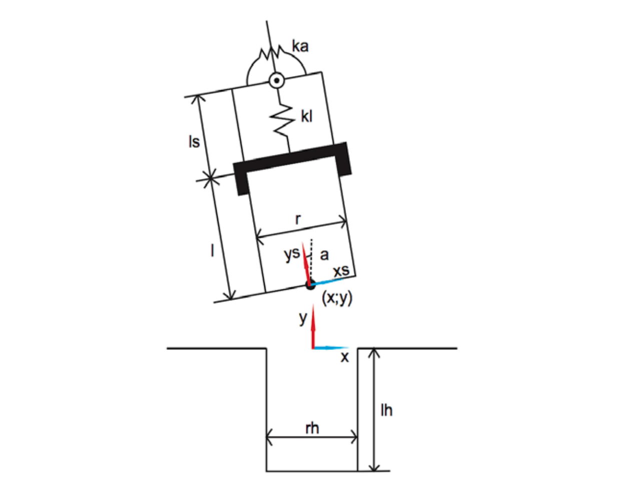
The insertion model for a piece in a hole can have a lot of shapes including rectangular, circular or even more complex forms. In this case, the easiest model in 2D is taken, which is the coupling of a rectangular piece and a rectangular hole that is slightly bigger. The gripper is considered rigidly and the sensor is modeled like a spring [11].

A. Variables

The simulation in Matlab requires variables for modeling a piece and its environment. In the Figure 5, the main variables for the process are shown, which are further described. These variables are kept constant throughout all of the simulations. The Figure 5 presents the coordinate (*x; y*), which is the position of the middle point of the piece. The degree to the global *y* axis is represented by *a*, the radius of the hole as *rh*, the radius of the piece is *r*, the length of the piece without deformation of the spring is *l*, and the Hooke constants are *kl* and *kd*.

Other important variables involved in the deformation, *dx* and *dy*, represent the deformation of the spring in the *x* and *y* axes respectively; and this both are used to calculate deformation in the axes of the pieces, *dl*. The deformation of rotational spring is *da*.

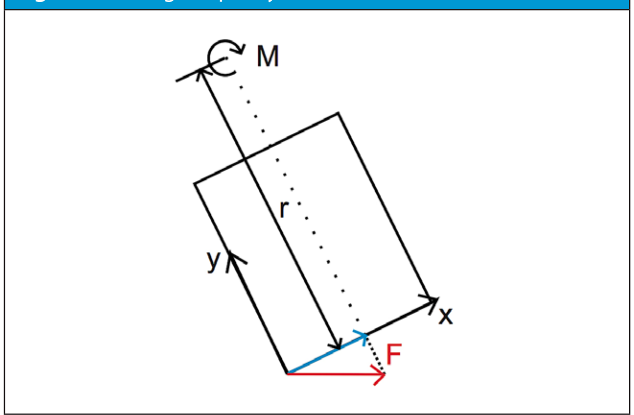
Fig. 5. Main variables in the simulation



B. Cases

The different configurations between the peg and the hole are described in 6 cases (Figure 7), depending on the peg's position relative to the hole and the direction of the movement. Based on these, reaction forces and torques are calculated, as well as the new position of the piece.

Fig. 6. Resulting torque by a contact force



The new position is calculated based on the collisions of the two components and the resulting deformations of the springs. At the beginning, the peg and the hole overlap, which is not possible in the real world. Therefore, the peg is moved in a single direction and produces a deformation in one or both springs. The force is calculated with the help of the Hooke equation (equation 1), but this force has two components. One is in the direction of the piece's axis and the perpendicular force. The last one produces a torque around the joint of the sensor (Figure 6). The torque is calculated around the center of the sensor as the equation 2 shows. Finally, the torque generates a rotation around one point.

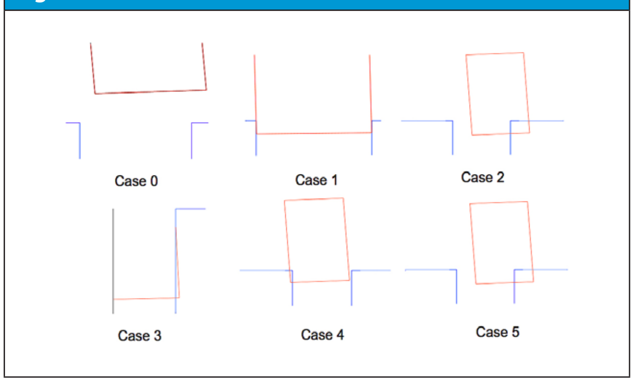
$$F = k\Delta x \tag{1}$$

$$M = r \times F = [x, y, z] \times [F_x, F_y, F_z] \tag{2}$$

The cases are (in all of them the peg and the hole only have one contact point, around which the rotation is made):

- Case 0: The peg and the hole have not contact.
- Case 1: The peg is inside the hole, the first deforma- tion is in x direction, and the torque is around the edge of the hole.
- Case 2: The peg is outside of the hole, the deformation is in ys sensor direction, and the torque is around the edge of the hole.
- Case 3: The peg is inside the hole, the first deforma- tion is in y direction, and the torque is around the corner of the peg.
- Case 4: The peg is outside of the hole, the deformation is in ys sensor direction, and the torque is around the corner of the peg.
- Case 5: The peg is inside the hole, the first deforma- tion is in x direction, and the torque is around the corner of the peg.

Fig. 7. Cases in the simulation



A flow diagram control calculates the new position and reaction forces according to the relative position between the peg and the hole.

C. Controller

The input/output values of the controller are presented in the ecuation (3), where the values in red are the new sensor position values. The green values are the old sensor position values and the black values are the measured reaction forces. The proportional constant, shown in capital letter, is multiplied with the reaction forces.

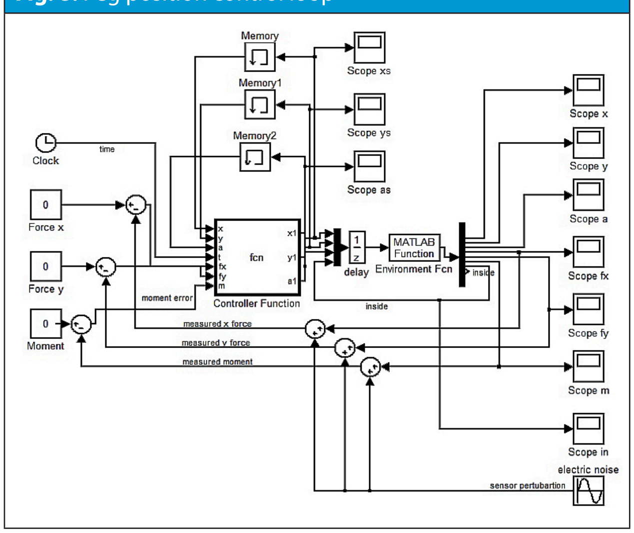
$$\begin{aligned} y &= -F_y \cdot f_y - STEP \\ x &= x - F_x \cdot f_x + M_x \cdot m \\ a &= a - M_a \cdot m \end{aligned} \tag{3}$$

There are two values in control of the *x* position because there are two parameters acting in two different situations. The *Mx* acts when the peg is not yet inside and the *fx* is too small for controlling the position. The *Fx* acts when the peg is inside and the *fx* is big and the *m* is small. A similar situation occurs with y position control, where the peg always has to go down with a variable step.

D. Control loop

The control of the piece's movement is important for the procedure with critical values such as speed, acceleration, forces and torque. All the processes can be controlled with the required specifications. This control does not consider the behavior of the robot, meaning that the robot is considered as a perfect machine without errors in position, speed, etc., and the application only takes care of the piece's movement.

Fig. 8. Peg position control loop



The first and most important block, as explained before, is the environment Fcn in the Figure 8. This environment block tries to simulate all the reactions that happen when two objects make contact, measured by a sensor, like in Figure 5. Another important block is the controller block, which tries to eliminate the reaction forces.

The delay block was placed between the controller and environment because the block of environment has to estimate the new values of the position. For this process, it requires a little time like in a real process.

IV. TUNING CONTROLLER

The tuning of the precise control changes the parameters of the controller in the control loop and determines whether the movement is stable, unstable, or unable to reach the hole. In the case when the control loop is stable, an important parameter is the time needed to go inside.

The initial parameters for the simulation are: *kl* is 2000 *N/m*, *ka* is 20 *Nm/rad*, time *t* is 0.3 *s*, *x* is 11 *cm*, *y* is 0.4 *cm*, *a* is 2º, hole radius *rh* is 1,5 *cm*, the hole length *lh* is 6 *cm*, the peg radius *r* is 1.495 *cm*, the peg length *l* is 6 *cm* and the spring length *ls* is 5 *cm*.

For the selection of the best values Figure 10 was made. For the time *t*=0.053 *s*, all of the lines are stable except for the blue. The values are: *Fx* is 0.0001, *Fy* is 0.005, *Mx* is 0.004, *Ma* is 0.9000, and the step is 0.0005.

Fig. 9. Initial peg position in the simulation

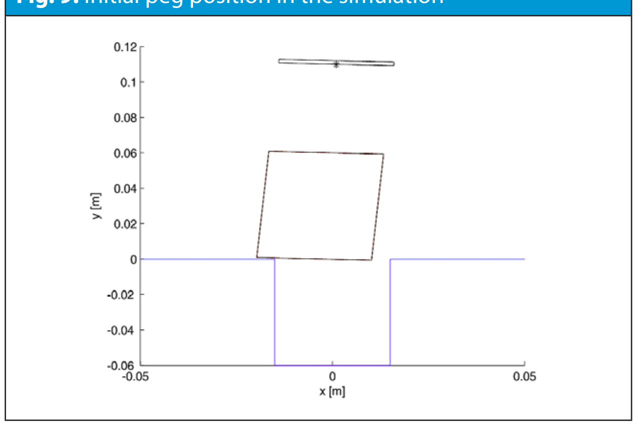
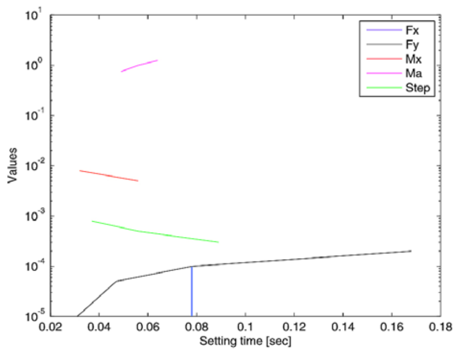
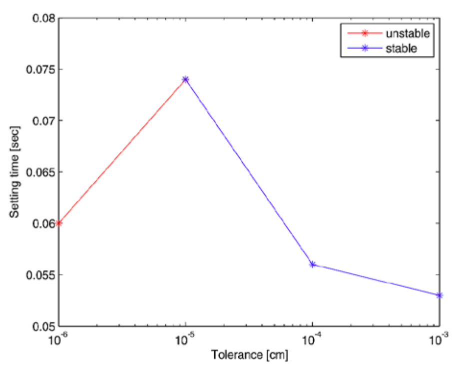


Fig. 10. Variation of the controller values



With these values, the control is relatively stable and the response with a tolerance of 1 *mm* is 0.53 *s*. If we decrease the tolerance, the setting time increases until it becomes unstable in 1 *µm* (Figure 11).

Fig. 11. Different tolerance for the mating process



V. SIMULATION

The simulation is initialized with position values, which are not in the correct position for mating the two pieces. Therefore, the piece has to move to the appropriate location. The point in the center of the piece marks the coordinates of the *x* and *y* values for the sensor (Figure 9).

The simulation time is 0.6 *s* and in this time the piece is arranged in the hole and also introduced a little. After this simulation time, there are no more significance changes between the pin and hole and the simulation is stopped. In the Figure 12, the final position is shown after 0.3 *s*. The lateral walls of the non deformed peg touch the walls of the hole, but the springs show the same reaction as if the peg is already inside.

Fig. 12. Final peg position in the simulation

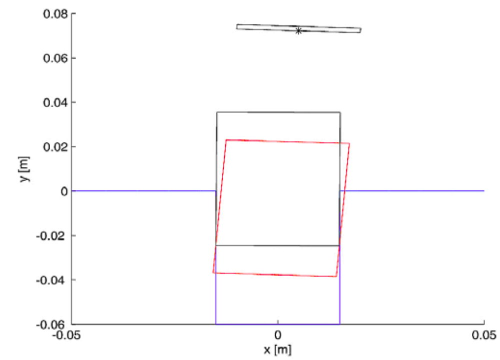


Fig. 13. Peg x position in the simulation

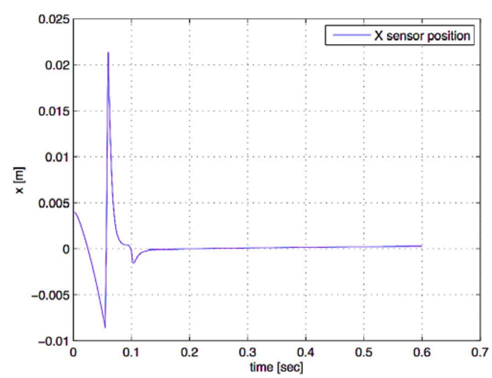
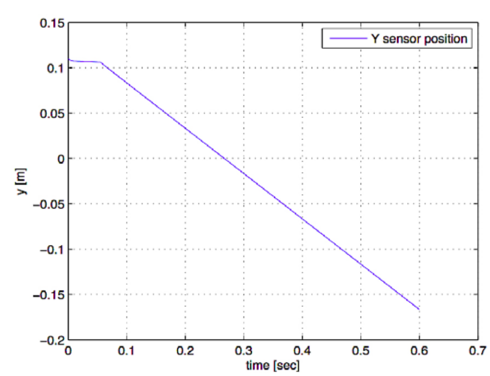


Fig. 14. Peg y position in the simulation

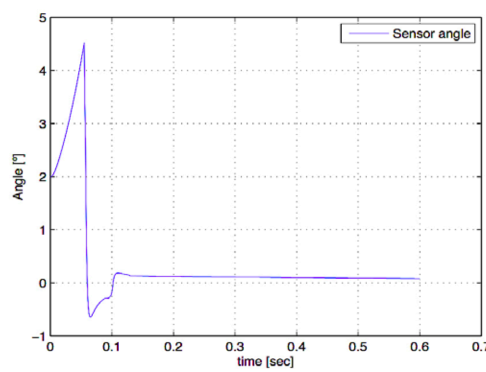


The coordinate *x* approaches zero gradually from 4 *mm* until 0.03 *s*. The time section, 0.03 to 0.1 *s*, is the most important part of the movement because it tries to align the pieces. After fluctuation in the range, the *x* position stabilizes in zero with only small waves due to the vibrations (Figure 13).

The *y* position is the direction where the object goes down, hence this curve represents the insertion movement. From zero to t=0.03 s, the control tries only to obtain the x position. After the 0.03 s, the movement in y direction doesn't have peaks and the peg goes down smoothly (Figure 14).

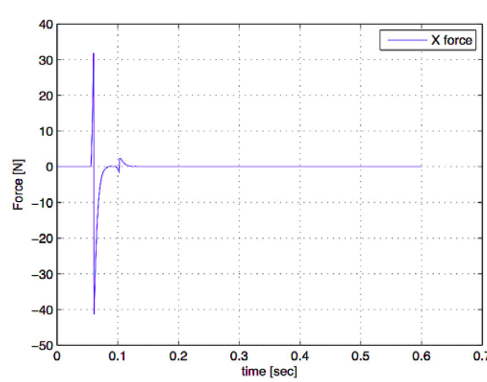
The Figure 15 shows the behavior of the angle. It began with 2° and reached a maximum value of 4.5° after the critical mated-process (peaks between 0.05 and 0.1 s). The angle tries to go to zero without perturbations, but is unable to because of the clearance between the piece and the hole.

Fig. 15. Angle peg/ground in the simulation



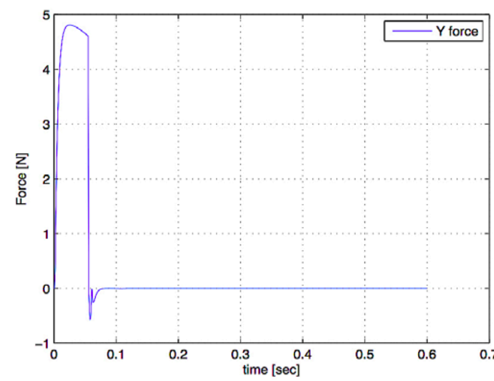
The force in the x direction of the sensor is presented in Figure 16. The force reaction starts with 0 N until the peg makes initial contact with the other piece. Afterwards the force has an extreme value until 0.1 s, when the pieces "finds" the hole. After finding the hole, the force goes back to 0 N. The piece collides with the left wall of the hole after approximately 0.05 s (positive peak) and later with the right one (negative peak).

Fig. 16. Sensor force F x in the simulation



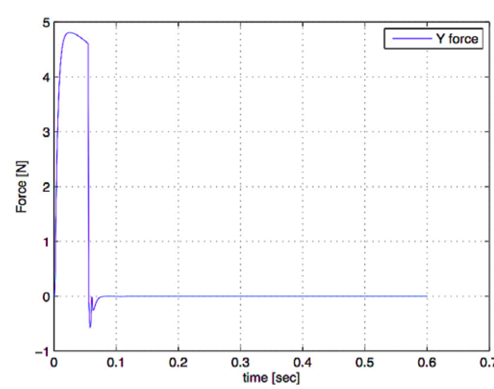
In Figure 17 the force in y direction of the piece is shown, it has one important peak between 0 and 0.06 s. It begins when the pieces make initial contact and the other peak is caused by looking for the correct position to enter.

Fig. 17. Sensor force F y in the simulation



The Figure 18 shows the behavior of the torque, which increases its values until 0.5 s. Later, there is a big negative peak and another small positive peak. At the end, the torque goes to 0 Nm. The first peak occurs when the peg touches the wall of the hole and the other occurs when the program tries to arrange the angle for the last time.

Fig. 18. Sensor torque M in the simulation



VI. CONCLUSIONS

With the establishment of contact conditions in various cases it is easy to generate a controller of the reaction forces. A method for generating the controller parameters for mating a pin into a hole is described in this article. The approach is presented by a reduced 2D model which will be expanded in the near future into a three-dimensional model. The main variables, tolerance and stiffness, are simulated in different forms.

Although the deformation of the piece's materials are not taken into account, a user can inspect the value of the forces to make sure that the pieces are not suffering damage. Also, the user can change the values of the controller factors and make the process faster or slower, depending on the situation. The design of the controller shows that the parameters are dependent on the geometric characteristics of the hole, the peg and the sensor. That means that the controller has a range where the control is valid and another where it is not. This range can increase if the setting time is decreased and conversely.

The results of the simulation separate into two clear behaviors of the insertion: First, when the piece is not inside and the other when it is inside. If the first process is unstable, the peg doesn't reach the hole. If the second process is unstable, the peg goes out of the hole because of the large variation in the x position. This model opens the door for making a controller like a PID control or even more advanced, like fuzzy control. This case has been approached by many papers and it is prevalent in numerous forms of literature.

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