Establishing Study of automatic control drilling applying on micro-robots

Paul Ciprian Patic, Mihaita Ardeleanu, Lucia Pascale, Florin Popa

***Abstract*—**A micro-assembly station based on a micro-robot, under an optical microscope, is one of the typical styles to practical application of the task of assembling simple micro parts, even if they are still almost at the start phase. The demand for the manufacture of micro components is increasing because many products are slim due to their portable use. A new production system is an interesting time in micro-assembly systems. The performance of the micro-robotic system has the potential to have an important role in such applications with reference to the transportation, handling and storage of micro objects. For that, has developed an automated system consisting of multiple drilling micro-robots. In this paper, with the aid of the control of "cluster" type for more micro-robots may deduct an execution of an application by drilling into the work area. This control "cluster" type may provide some advantages having in view the accuracy and flexibility of micro fabrication. This study is a continuous our work in micro-robots domain, here one developed the automatic control drilling from electronic and informatics point of view.

***Keywords*—** Actuator, Drill, Micro-controller, Micro-robot.

I. Introduction

FOR modern portable consumer product applications, development of production facilities for assembly and production of miniature components are a great interest because one of the major orientations in the industry is to manufacture smaller products at low prices. In fact, with the increasing of this miniaturization, it is known that it will be more difficult for conventional sized mechanisms to manipulate and assemble the small pieces of work, as they will hit the mechanical limits of accuracy due to manufacturing errors, friction and thermal expansion, as high energy consumption during operation.

This work was created after a long research together with a small group of students from our faculties.

Paul Ciprian Patic is with Valahia University of Targoviste, Electrical Engineering Faculty, Automatics, Informatics and Electrical Engineering Department, 18-24 Unirii Boulevard, 130082, Targoviste, Romania (e-mail: patic@valahia.ro).

Mihaita Ardeleanu is with Valahia University of Targoviste, Material Engineering, Mechatronics and Robotics Faculty, Mechatronics Department, 18-24 Unirii Boulevard, 130082, Targoviste, Romania (e-mail: miniarde@yahoo.com).

Lucia Pascale is with Valahia University of Targoviste, Electrical Engineering Faculty, Automatics, Informatics and Electrical Engineering Department, 18-24 Unirii Boulevard, 130082, Targoviste, Romania (e-mail: p_lucia@valahia.ro).

Florin Popa is with Valahia University of Targoviste, Material Engineering, Mechatronics and Robotics Faculty, Mechatronics Department, 18-24 Unirii Boulevard, 130082, Targoviste, Romania (e-mail: p_florin@yahoo.com).

Donaldson, in 1986 shows that, even if will be possible the improvement of machine performance, then it will be higher costs for maintenance. As an alternative solution to this problem, miniature robots which are equipped with micro-sensors, manipulator and tools may have an effective role in such a small scale production system with greater flexibility and reduced cost.

A micro-assembly station based on a micro-robot, under an optical microscope, is one of the typical styles to practical application of the task of assembling simple micro parts, even if they are still almost at the start phase. On the other hand, practice production application, such as a micro-drilling operation, using conventional machine tools, is based on a combination of mechanisms for both spatial positioning tool and for the sample, relative to standardized mechanical cutting on different axes [5].

Previous study, having in view this kind of micro-robots, has been done using one type of drill micro-machine with some establish characteristics. Also, we used for determination a breviary of mechanical calculus, taking into account different forces, moments and mechanical constants.

The paper presents a concept of control for automated micro-drilling, "cluster" type, in which several miniature robots, piezoelectric trained, are used to transport the piece of work to hold and to permit the micro-borer introduction.

The micro-robots, which are formed from a pair of piezoelectric elements for smooth motion and some electromagnets for fixing on a mounting surface, are developed for a resolution of movement and positioning of sub-micron level [9], [10].

In the main experiment, automatic special task, to give more small holes under the supervision of the camera CCD, based on a feedback system, will be discussed to investigate the performance and feasibility.

The general task of automatic generation of the control tests for various object areas, allowing the creation of the single formalization based automatic test control systems. The control of models and adequacy of their realization always was regarded as an actual problem, because checking of the adequacy of the model realization is an informal, difficult, multi-factorial task. On the background of continually increasing the dimension of such problems, to make control more effective it becomes necessary to make testing control process automated. It is necessary to work out the principles of constructing the automated testing control systems and testing control methods for various object area formal models and adequacy of there concrete realizations. To organize the automated testing control it is needed to have tests with high completeness and efficiency [3].

For related auto parts industry, modularization and weight reduction of chassis subassembly are one of the main goals in order to achieve fuel efficiency and lower production cost. Additionally, auto makers also require that the part manufacturers to provide a subassembly unit defined by modularization [8].

A computational method for solving the dynamic equations of motion of manipulator-robots, using the integration methods can be made. The proposed algorithm is conceived using Mathematica software (for example) software, which allows the integration of differential system equations by his functions, assuring in this way the result correctness and a high computational speed.

The software may be used for the 2-D or 3-D robots manipulators, which contain an open kinematics chain with rotation and translation joints.

The software allows also for the calculation of the time variation curves of the degrees of freedom, having as initial data the values of joints generalized forces, the mass and inertia of the robot links, the inertia of the actuators and the initial conditions for joints coordinates and speeds

The dynamic simulation of micro-robots represents the integration of the differential equation system, considering like inputs loads and actuator torques vector from manipulator joints. The dynamic simulation problem represents the direct dynamic model design having like solution the manipulator behavior [3].

A. Dynamic modeling of industrial robots

The dynamic modeling of robots [11], [13] represents the determination of the dynamic equations, which is the first information necessary for robots control [3], [6]. These equations are useful for computational simulation of the robots motion and for the evaluation of kinematical structure of robots [3]. In the dynamic formulation of manipulators the following methods are used: Lagrange-Euler, Newton-Euler, D'Alembert. In [11], [13] reference books there are discussed only plan manipulators with 2 degree of freedom. For the manipulators with more than 2 degrees of freedom (DOF), a very laborious calculation is necessary. The Lagrange-Euler method is relatively simple and systematically. As a rule, the dynamic for a device of electronic control and the frictions of gearing are not considering. Thus there is obtained a 2nd degree equation system. For the robots with 6 degree of freedom, the dynamic equations are nonlinear and very laborious. Generally, each term of the inertial force and gravitational force depend of the instantaneous position of the kinematical links; the terms moment and force depend on the velocity and the position of kinematical links. The dynamic equations are obtained by the Lagrange-Euler method for the non-conservatives systems. If the non-dimensional method is used, the dynamic formulation is more efficient. The new method of kinematics and dynamics modeling use the homogenous matrix and the Lagrangean formulation [6].

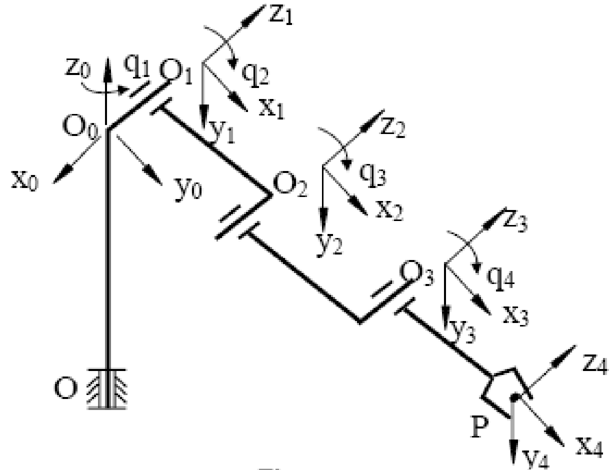

Fig. 1 The 4R spatial manipulator

The D-H method was used buy many researchers for the study of kinematics and dynamics of manipulator robots. It forms the basis for the following programs GESIMA (GEometric SImulation of the MAnipulator), SPHEMA (SPHEres Manipulator), IKIREM (Inverse KInematics REdundant Manipulator) which solves the inverse kinematics for a redundant manipulator by utilizing the optimum simulation of the system manipulator – obstacle [5].

The proposed algorithm and program for the dynamics calculation of the manipulator-robots has input and output data [6].

The input data are: D-H parameters; the coordinates of mass center for each kinematical link; the inertial couples axial and centrifugal of each kinematical link; the inertial motor (actuator) couple for each joint; the vector of gravitational acceleration.

The output data are: the geometric - kinematical model; the effective inertial force or couple of each joint;

the inertia of coupling between the joints i and j; the centrifugal force of link i due to speed of joint j; the Coriolis force of the joint i due to the speeds of joint j and k; the gravitational loads of each joint; the manipulator – robots dynamic equations.

The notations used in computational program are [5]:

$m[i]$ - the mass of i kinematical link;

g - the gravitational acceleration vector, with respect to the fixed-reference system;

$q[i][t]$ - the generalized coordinate of kinematical link as function of time;

$Q[i][t]$ - the generalized force of joint i corresponding the independent parameter $q[i][t]$.

It is consider, as example, a planar manipulator 3R (Figure 2) actuating in the vertical plan [6].

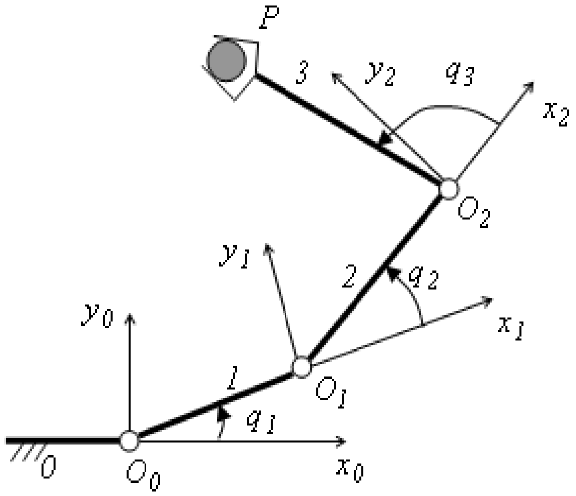

Fig. 2 Trimobil planar manipulator 3R

The optimum position of an industrial robot in respect to the given application is a very important problem, which can not be solved without a complete analysis of the robot working, from the kinematics and kinetic-static point of view.

The optimum position of the robot frame in respect to the given application is determined so that [7]:

- the robot productive rate must be maximum, i.e. the time of a duty cycle must be minimum;
- the energy consumption for a duty cycle must be minimum;
- the maximum power consumed during a duty cycle must be minimum;
- the maximum driving force or moment from the driving system, measured during a duty cycle, must be minimum.

B. Robotized Technological Process

Here, it is presented a possibility, proposed for establishing the sequence of the operations for the technological process. The most important, from the technologic engineer point of view are the information that is related to manipulation and orientation of the work piece. That information must be related to workspace of the robot and the workspace of the machine tools [7].

This class of systems is well represented by differential model as a set of nonlinear differential equations with given initial conditions and sub-optimality intervals for state variables.

C. Kinematics analysis of industrial robot mechanisms

In order to determine the above mentioned objective functions it is necessary both the kinematics analysis and the kinetic-statics analysis of the robot mechanisms. It is assumed that the dimensions and masses of the component elements of the industrial robot and of the manipulated object are known. Also, it is considered a variation function for the independent variables with respect to the time. Generally, the dependence with the time of an independent variable (generalized coordinate) may have any form. The choice of the optimum function for certain goal is made in concordance with the motion type, maximum and minimum values of the relative speeds and accelerations and with the continuity conditions from the acceleration diagrams [6]. One of the functions, $s = s(t)$, is make from three sectors, namely accelerated motion sector, uniform motion sector and decelerated motion sector (Figure 1). The acceleration and deceleration are constants. This function has the advantage that, for a certain value of the maximum speed, the acceleration and deceleration values are the smallest [7].

In a similar manner, the acceleration and deceleration times is calculated in the event that the active kinematics pair is a revolute one, in terms of the relative rotation angle magnitude and the maximum angular acceleration [7].

In the inverse kinematics analysis of a mechanism are established the variables of the driving kinematics pairs in terms of the position of a point of a element or as function of the position of a coordinate axes system assigned of this element.

The problem has solutions only if the freedom degree of robot [7].

In this paper, our actual research is based on including in technical part of an electronic and informatics modules to make more easy the next steps for the final application, such are the automatic control in drilling operations.

II. Drilling operations Realized by a Robot

It is known that the characteristics of the robots, in general, are utilized to give a flexibility to the system and, therefore, the complexity of the robotic model is increasing slower with the number of degrees of freedom, compared with the general type of some manipulators [12].

In Figure 3, is illustrated an overview on a micro-drilling system, being in development, based on micro-robots. Each of the small robots, used in this system has a pair of electromagnets and piezoelectric elements to move precisely as an "inchworm", and is specialized to handle one or two specific operations [14], [22].

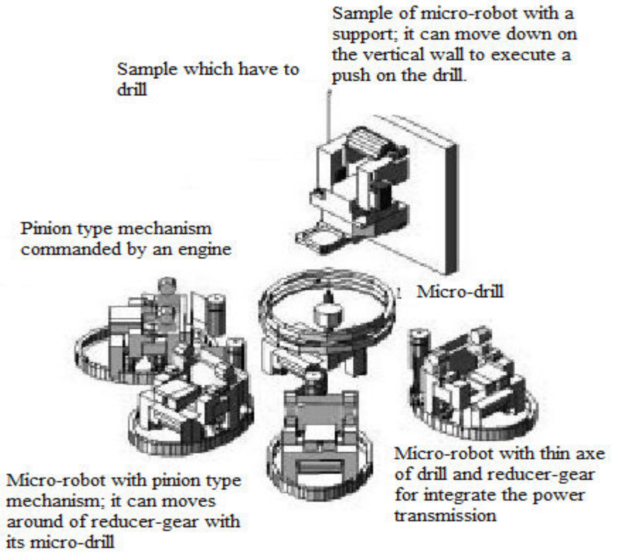

Fig. 3 The assembly of a micro-drilling system based on micro-robots

This mechanism can provide fine mobility with step by step microscopic motion and stable clamping on such a surface during operation, even on vertical walls and ceiling, all over on the vast working space, even if the target area is limited to ferromagnetic surfaces. In an input voltage of 100 V on piezoelectric element, the typically step is about 10 microns, so it can move at a speed of 1.5 mm / s when is activated a frequency of 150 Hz [Aoyama *et al.,* 1993].

Also, the different pitch of each piezoelectric element can command the direction of motion. However, the electricity and the robot control signal are transmitted by wire, because of high voltage sent to the piezo-element and high amperage sent to the electromagnet, this should be improved in a future by advanced technology [10], [14].

In such robotic systems is essential to incorporate visual monitoring tools, such as CCD camera, and computer resources to control them, but this system is very complicated. Therefore, it is developed a simple navigation system, of acoustic type, for example. To achieve the proper task of drilling have been developed three types of micro-robots [9], [14].

One of them is equipped with a thin drill, with the gearbox on axis; the others have the shafts mechanisms commanded by D C micro-engines. The little part that will be holed is going to be held by the micro-robot who can move even on the vertical walls. After that, the product positions and the drill characteristics are fairly fixed, the micro-robots with engines can approach by the robot with drills for drilling. Then the robot from vertical wall can carry the piece down to the drill and carefully push for a hole from start to finish [10], [14].

A. The control system distribution

It is well known that always the control of several robotic systems have one of the biggest problems because it contains many points of difficulty and complexity of robots command; planning and programming, operations allocation, communications, and problems of other areas [9], [10].

In order to get the operation required, a part of the control system is taken into account from the beginning, so that the system can be partially centralized and partially distributed. It is expected that the combination of centralized and the distributed architecture can provide effective solution to the multi-robot systems.

In Figure 4 are shown some robots which are organized having in view the control system [14].

To avoid the complication or increasing of the price system, a monitoring CCD camera is mounted at an angle of 45 ° on a framework, the purpose of that is to monitoring the robots in horizontally and vertically plans.

The image of the camera from the robots with the drill machine from horizontal plan and the vertical plane model, can be extracted and the coordinates x - y can be passed to a central computer using image processing tools in real time that are able to reach a the resolution of 5000 x 5000 with a refresh rate of up to 60 Hz.

Because this framework can cause image distortion the numerical compensation is taken into account to obtain details of individual geometric positions of the two robots. Thus, total accuracy is expressed in an area of 0.1 mm to 400 x 400 mm^2. However it is essential to implement advanced systems to measure spatial positions [9], [10].

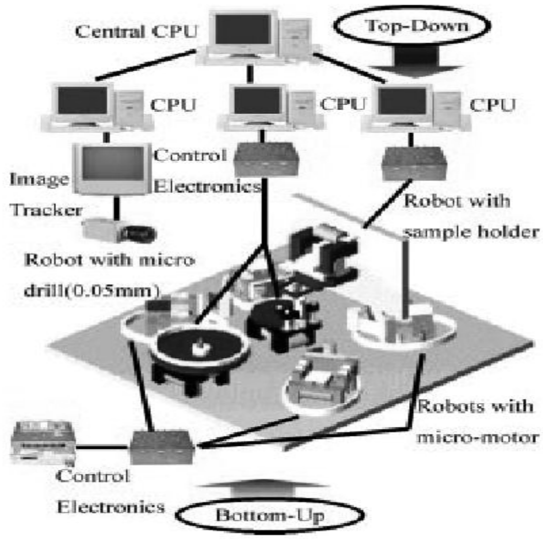

Fig. 4 Control systems incorporating the monitoring system with CCD and several Computers

B. Guidance with acoustic signal

Instead of visual inspection, orientation with the acoustic signal is also used for simultaneous control of several micro-robots driving with DC motors. These micro-robots can easily move forward to reducing gear and then return after the operation.

A sound sign by 1 kHz which is generated by acoustic sources in the central part of a drilling reducer-gear can be monitored by micro-robot's microphones so that each robot can move automatically switching the piezoelectric elements.

This simple driving may cause collisions between micro-robots as they all close by the same target. It is known that they are not endowed with the functions to avoid the impact. Because the speed of the micro-robots is very small there will be no damage from the impacts.

Having in view the micro-robot's drive to the reducer-gear drilling, the technique of guidance using outdoor framework is applied complementary with the acoustic guidance system.

Guidance with ellipsoidal outer frame on the smooth collision model

To investigate the behavior of trajectory after the collision of micro-robots is present such a model in Figure 5 [14]:

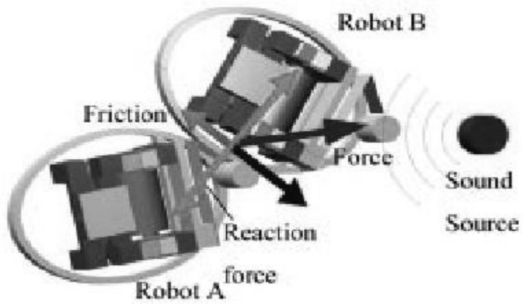

Fig. 5 Simple collision model of a two micro-robots

One expects that two micro-robots which come into contact to generate a pushing force on each other. Micro-robot can still make a displacement to the source of acoustic signal along the other micro-robot's framework.

Using a simple mathematical model, simulation can show the trajectory of possible motion with respect of: the focal point, the angle of impact, the coefficient of friction, and the elliptical curve. The result of such simulations is shown in Figure 6 the micro-robot collides of other micro-robot and then continues its path to the source of signal noise [14].

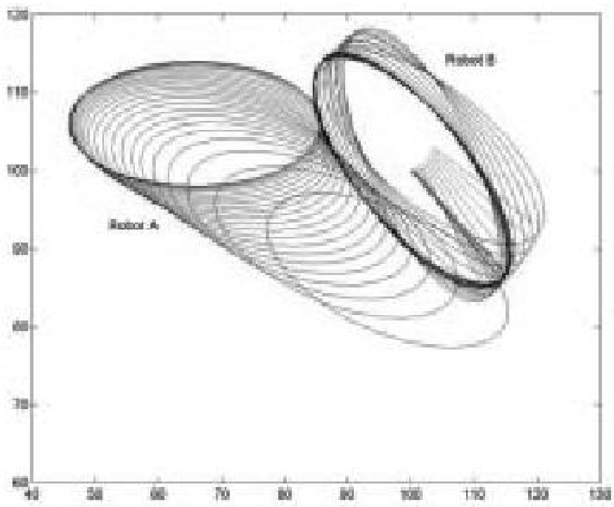

Fig. 6 The result of simulation of a model of acoustic navigation after the collision

It is obvious that micro-robots are moving in accordance with the influences, such as: the principle of action and reaction forces, the moment of inertia and friction forces. However, in certain conditions, such as orthogonal collision or focusing of more robots, the blocking of robots is expected. In such cases will be implemented other control systems.

III. Case Study

In this paper we try to introduce the control multiple systems of a micro-robots for micro-drilling operation. Each micro-robot has a reducer-gear with a micro-drill, a reducer-gear assembly operated by a DC micro-engine, an acoustic orientation and monitoring system, which is implemented to provide a combination of centralized and distributed control. In order to improve efficiency and accuracy, it is developed the precision of measuring instruments, elements of local sensors and the property to make the recovery from blocking state.

According with other our research, we establish new characteristics for the technical theme. Also, one elaborates an informatics and electronic concept used in command and control program of drill micro-machine, developed below.

A. Detailed technical theme

It will design a drilling micro-machine with features:

1. Assigned to a space with dimensions: 100 mm x 50 mm x 35 mm
2. The maximum displacement of a drill c_{bu} = 1200 µm
3. The minimum pushing force on drilling operation F_{amin} = 0,1 N
4. The maximum speed on drilling operation n_{max} = 4500 rpm
5. Increment of linear displacement i = 10 µm
6. User interface specifications:

6.1. Button --- Manual command for linear displacement - "attack" sense;

6.2. Button --- Manual command for linear displacement - "retraction" sense;

6.3. Button --- Manual command - 1/2 rotation drill sense;

6.4. Button --- Manual command – increase drill speed variation;

6.5. Button --- Manual command – decrease drill speed variation;

6.6. Button --- On/Off command, lighting system of the operating area;

6.7. Button --- On/Off command for whole system.

7. The enclosure that includes the operation area will be equipped with an optical system and camera
8. Lighting system will be punctual focusing on the working area, photo-luminescent diode light source, and white light optical focused
9. The command for linear displacement will be realized with PWM (Pulse Width Modulation), tact generator will be the PIC16F877A micro-controller (a very used one in robotic guidance)
10. The command for drill speed adjustment will be realized with PWM, tact generator will be the PIC16F877A micro-controller
11. The used software for micro-controller programming: MIKROPASKAL (this is easy to use and may have many applications in robot modeling [5])
12. The adjustment modules will be separated.

B. The informatics concept used in command and control program of drill micro-machine

The hardware includes two PWM generators modules, separated from each other so that the problem is reduced to a computer running the same program on two different hardware units.

The essential parameter is F.U. Its varying will be incremental, with a quantum set at a value agreed and appropriate application.

The growth of the factor F.U. lead to higher potential energy storage in the arc, through its deeper strain, the electro-magnetic developing a greater force, the supply of the coil is done at a higher effective voltage.

In Figure 7 it is shown the logical of PWM command.

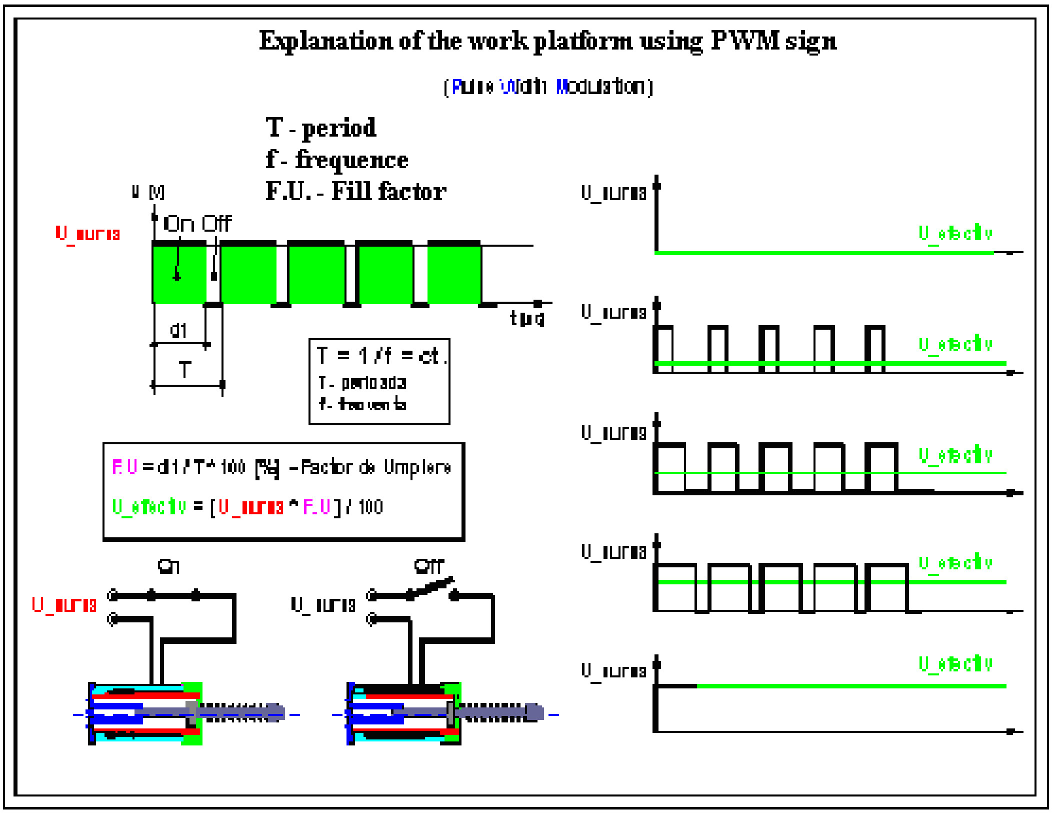

Fig. 7 The logical of PWM command

C The problem's analysis

The hardware components includes: two PWM generator engines, which are separates one by each other units, so that the informatics problem is reduced to a same program that run on two different hardware.

The essential parameter is F.U. (Fill Factor). Its variation will be incremental, with a quantum set at an agreed value and appropriate application.

The growth of the F.U. factor, lead to higher potential energy storage in arc, by its deeper strain and those the electro-magnetic force developing a bigger force and the coil's alimentation has done at a higher effective voltage.

In Figure 8 is presented the logical algorithm for P.W.M. program.

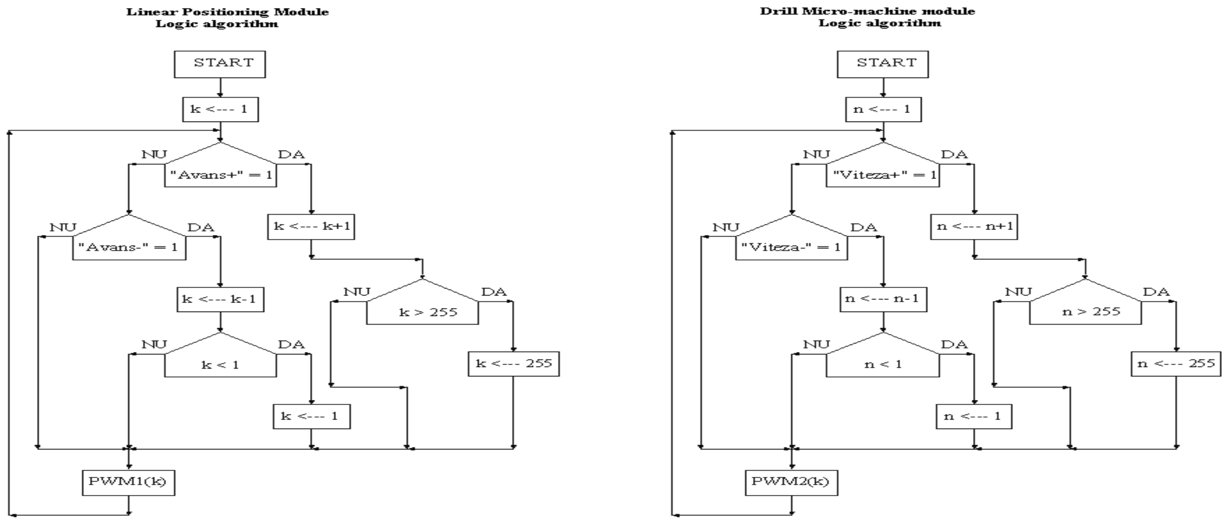

Fig. 8 The logic P.W.M. Algorithms for two hardware units

D The electronic concept for the command and control hardware of the drill micro-machine

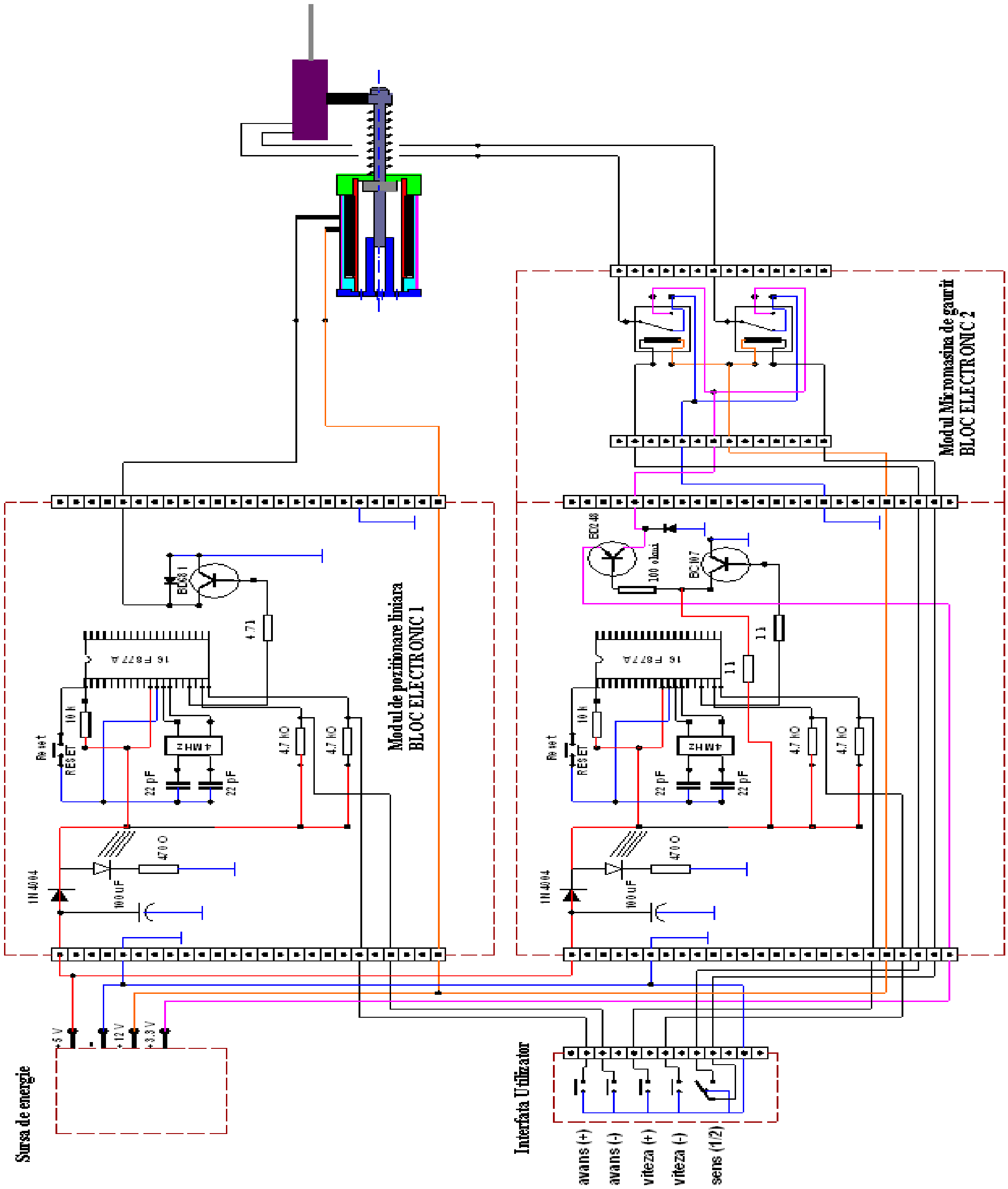

Fig. 9 The electronic scheme of a drill micro-machine

The Hardware is two identical modules which includes, like central element, one PIC16F877A microcontroller each, difference being for the output segment. One module has an output a PNP transistor and the other one has an output a NPN transistor.

Each module is connected to user interface through links of "Button" type, by these inputs it is launching the control signals that are described, in detail, above in technical theme.

Changing the rotation direction of DC motor which is acting micro-machine's drill is done through an "H" bridge made with two relays. Each relay contains one normally open contact and one normally closed.

Normally open contacts will connect to the supply voltage + Vcc, and the normally closed one, will connect to the null.

The voltage level +Vcc are PWM modulated by the output PNP transistor module.

In figure 9 is presented the electronic scheme that was realized especially for this work.

IV. Conclusion

The Micro-Robots field is belongs to the future, its applications will govern the scope of industrial and social activities.

The prototype developed is a technical platform that enables the development of some accuracy studies of micro-positioning with a large impact on the design of new command and control hardware units. The prototype made open the way for laboratory applications, which can exemplify the working principles of this technical field of great importance.

The idea of viewing the command effects of micro-machine through a web-cams and a magnifying optical system, has made significant contributions to the technical quality of the prototype. Future research directions that will develop from this application refer to a series of studies of repeatability precision, with an impact on the experience in the construction of micro-machines. Also, we will try to make an interface, which may command two or many micro-robots who make different drilling operations, using a radio or infra-red remote control.

In comparison with the software designed using classical programming languages like Fortran, C (and different versions – C++, C# etc.), Pascal etc, the proposed software is conceived in an advanced programming language for mathematical computation and allows the design of the converse geometry model for redundant structures in a very short computational time. The proposed software allows for the determination of dynamics errors and the influence of each geometric, kinematics or dynamics parameter.

The proposed software allows also studying the influence of the change of initial conditions, generalized forces from joints and links masses on the diagram of command functions.

The proposed software is easily to use and may have many applications in robot modeling.

Robot Drilling provides the best alternative to the taxing, and often dangerous work of manual drilling. Not only have companies improved drilling accuracy, repeatability, and speed, but they have increased productivity and savings.

The drilling robots work without growing tired or taking a small or long break. This increases operational output as drilling cycles occur faster and more reliably.

Other future research will be passing from classical method of drilling to a new one named Laser Drilling. One can be realize one or many micro-robot(s) features with laser drilling end-effectors. Like an application developed can be produce micro-holes in almost any material, wood, plastic, steel etc.

References

[1] Ardeleanu M., Gheorghe G., Matei G., *Mecatronics. Principles and applications.* Edited by AGIR, 2007.

[2] Bishop Robert H., *Mechatronical handbook*, The University of Texas at Austin M. K. Ramasubramanian North Carolina State University.

[3] Bosikashvili Zurab, Kapanadze David, Zhvania Taliko, *About Conceptual Model of the Test Control Problem,* Proceedings of the 4th WSEAS International Conference on Computational Intelligence, CI '10, April 20-22, Bucharest, Romania, p. 39-42, 2010.

[4] Dale C., Nitescu Th., Precupetu P., *Industrial technical Drawing for machines buildings,* Ed. Tehnica, 1990.

[5] Filip V., Neagu A., *A Symbolic Computational Method for Dynamic Simulation of Multibody Systems,* First International Conference on innovative Computing, Information and Control – Volume I (ICICIC '06), Beijing, China, august 2006, p. 130-133, ISBN 0-7695-2616-0.

[6] Filip V., *Dynamic modeling of manipulators with symbolic computational method,* Proceedings of the Romanian Academy, Series A, Volume 9, Number 3/2008, p. 237-242, ISSN 1454-9069, 2008.

[7] Ion I., Dinu C., Vladareanu L., Lupeanu M., Vasile A., *Positioning and Displacement Issues on Optimizing Industrial Robots in an Aided Manufacturing System,* Proceedings of the 9th WSEAS International Conference on Application of Electrical Engineering, AEE '10, March 23-25, Penang, Malaysia, p.233-238, 2010.

[8] Jong-kyu Kim, Seung Kyu Kim, Hwan-Jung Son, Kwon-Hee Lee, Young-Chul Park, *Structural Design Method of a Control Arm with Consideration of Strength*, Proceedings of the 9th WSEAS International Conference on Applied Computer and Computational Science, ACACOS '10, April 11-13, Hangzhou, China p. 149-152, 2010.

[9] Patic P. C., Ardeleanu M., Popa F. - *Micro-Robots used in Control of Automatic Drilling Operations*, WSEAS TRANSACTIONS on CIRCUITS and SYSTEMS, Issue 6, Volume 9, ISSN: 1109-2734, June 2010, p 420-429.

[10] Patic P. C., Ardeleanu M., Popa F., Pascale L. - *Study Regarding the Establishing of Automatic Control Drilling on Micro-robots,* International Conference of the Institute for Environment, Engineering, Economics and Applied Mathematics: Circuits, Systems and Signals" (CSS 2010), La Valetta, Malta, September 15-17, 2010, ISBN 978-960-474-217-2, ISSN 1792-4618, p. 122-127.

[11] Patic P.C., Popa F., Ardeleanu M. - *Control of Automatic Drilling Operations with Micro-Robots,* 10th WSEAS International Conference on ROBOTICS, CONTROL and MANUFACTURING TECHNOLOGY (ROCOM '10), Hangzhou, China, April 11-13, 2010.

[12] Popescu M. C., Borcosi I., Olaru O., Nicolae A., *Simulation of n-r robots,* WSEAS Transactions on Systems and Control, v.3 n.3, p. 149-158, March 2008.

[13] Vladareanu L., Tont G., Ion I., Velea L., M., Gal A., Melinte O., *Fuzzy Dynamic Modeling for Walking Modular Robot Control,* Proceedings of the 9th WSEAS International Conference on Application of Electrical Engineering, AEE '10, March 23-25, Penang, Malaysia, p.163-170, 2010.

[14] Tokuji Kuronita, Shigeru Tadokoro, Hisayuki Aoyama, *Swarm Control for Automatic Drilling Operation by Multiple Micro Robots*, Proceedings Australian Conference on Robotics and Automation, Sydney, 14-15 November, 2001, pp. 7-12.

[15] http://www.i-swarm.org/

[16] http://lsro.epfl.ch/page62453.html

[17] http://www.amir.uni-oldenburg.de/

[18] http://www.iris.ethz.ch/msrl/?page=

[19] http://micro.seas.harvard.edu/?page=The

[20] http://www.cse.ucsd.edu/~gill/

[21] http://robotics.eecs.berkeley.edu/~ronf/milli-robot.html

[22] http://www.csem.ch/fs/microrobotics.htm

[23] http://www.microrobotics.co.uk/