Proceedings in MANUFACTURING SYSTEMS Proceedings in Manufacturing Systems, Volume 6, Issue 2, 2011 ISSN 2067-9238

PATH PLANNING ALGORITHM FOR HYDRO-MINA ROBOT OPERATING IN MICRO AND NANO ENVIRONMENTS

Daniel PENCHEV[1,*]

[1)] PhD Student, Institute of Mechanics, Bulgarian Academy of Sciences, Sofia, Bulgaria

Abstract: *In this paper some path planning algorithms are describe for Hydro-MiNa robot motions in micro and nano technological environments. This is a part of a project for creation of human-machine interface with force feedback for handling of micro and nano objects. The main purpose of path planning algorithms using here is to increase the ability of the tele-operator to rich its targets at the stage operating by the robot Hydro-MiNa. Due to very small sizes of the investigated objects the exact operator actions are with full significant for decreasing the mistakes and improving the speed and accuracy of the operations. To reach the solution of path planning task the Voronoi Diagrams method is utilized because although it is very old and well known algorithm it has been proven itself as a very effective one. This method is combined with A-Star algorithm for searching the shortest path from current operator position to the object and optimize it in order to avoid most obstacles occurred on the stage.*

Key words: *path planning, Voronoi's diagram, planning algorithms, virtual reality, micro/nano robot.*

1. INTRODUCTION

Nanotechnologies have emerged as a new frontier in the science and technologies. The advantage of nanotechnologies is that we are working on the molecular level atom by atom and it is possible to create large structures and devices with very different molecular organization and characteristics. Therefore, nano-technologies have a large influence in different science spheres.

To achieve cost effectiveness in nanotechnologies it is important to automate actions in nano scale. The engineers need to construct robots which manipulates in nano scale. On one side researches are for understanding of physical and chemical interactions in nano world, and on the other side it is important to be constructed new ways, new controls and sensing technologies and human-machine interfaces in nano world.

The best solution is if the operator can works into nano world as he works into macro world. However there are lots of different force interactions and physical laws into nano world that have to be taken into consideration during the tasks in nano-environment [1].

Virtual Reality technologies (VR) afford an opportunity to the scientists to expand their abilities in sense and manipulations into the nano world. The main purpose is that all object manipulation actions -positioning, assembling, grip, release, adjust, fix-in-place, push, pull etc. in macro world to be given up to the operator when he works into nano-environment.

VR is a 3D computer simulation of the studied stage where the operator may operate like he is into the nano world. The limitations into nano-environment have to be translated correctly into the Virtual Reality scene, so that the operator feel himself as closer to the nano world as he can investigate it free and comfortable. Therefore force feedback devices with haptic human-machine interface are using for researches.

Nano objects show different mechanics from macro sized objects. For example, adhesive surface forces dominate over inertial forces at nano-scale. In addition, there are non-contact forces such as Van der Waals, capillary, and electrostatic forces [2]. When working into nano world crucial the accuracy of the actions and "sterility" of the stage. Although all measures taken will necessarily encounters obstacles at the working area-particles of dust or other nano particles. If motion of probe tip is not enough carefully it may has been broken or other particles would adhere to its surface and it will confuse the operators work.

At the nanoscale, tasks are defined as conventional ones such as positioning, assembling, grip, release, adjust, fix-in-place, push, pull, and so forth of individual n-objects [3]. All these tasks should be done fluently over each of nano objects at the stage. Therefore the maximum accuracy of operator motion is very important. While the probe tip is working into the nano environment and is passing between nano objects it has to be done very carefully. On the one hand so as not to encounter any unwanted particles, and the other the operator to be able to operate with the studied object in the most precise and efficient manner. Therefore the process of the tool path planning in the scene and the subsequent removal of the operator to the target are very critical. In the current article we will examine various proposals for a solution to this problem. We are based on specific task – cells injecting with micro needle. We are using a force feedback joystick for control of needle stick motion.

The specific problem that should be resolved is just helping the operator to reach the sites of injection into

[*] Corresponding author: acad. G. Bonchev St., Block4, 1113 Sofia,
Tel.: +359-2-8706264
Fax: +359-2-8707498
E-mail address: *daniel.penchev@gmail.com* (D. Penchev)

the nano environment and ensure accuracy during releasing the cell. The technological dimensions of the probe tip are so small that if you do not specify the angle and intensity of pressure at puncture, not operation can be performed and the needle will break itself. Furthermore, as mentioned above and because of the inability to provide sterile environments for the staging the path that will be guided needle should be maximal accurate and "safe".

2. MECHANICAL MODEL OF FORCE INTERACTIONS IN NANO ENVIRONMENT

Before considering the algorithm of path-planning for research it is important to describe the forces between particles into the nano environment.

There are three major forces models into the nano environment:

- Probe tip – nano object (shown on the Fig. 1.) The model of non-contact forces interaction is similar than the model of contact forces interaction. Acording to the notations in Fig. 1, the forces *Fta* and *Ftr* are respectively the adhesive force between the tip and the nano object and repulsive force over the object. *Fsr*, *Fsa* and *Fsf* are the forces which describe the interaction between nano object and surface of the stage. The friction force is *Fsf* while *Fsr* is the reflection force between the surface and the object. *Fsa* is the adhesive force that is available in nanoworld interactions.
- Nano object – substrate– during manipulations the particles are in continuous contact with the environment where they are located, so the forces of friction and contact forces have to be considered.
- Probe tip and substrate – contact and non-contact force interactions should to be investigated to be able to show the stable stage of the model.

The force interactions models in the nano environment are shown in Fig. 2. The marked forces are as follow: *a* – adhesive, *f* – frictional, *r* – repulsive. The forces applied to the tip should be balanced by the normal force *Fl* and the lateral force *Fz* which becomes from the tip hook [2]. The balanced tip has conditions by *Fz* and *Fl* directions and using the Newton laws for static it is easy to determine:

$$Fl = Ftsr - Ftsa\,. \quad (1)$$

$$Fz = Fta - Ftr + Fsf \quad (2)$$

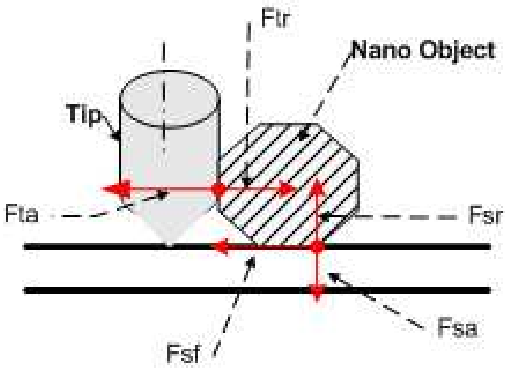

Fig. 1. Probe tip – nano object.

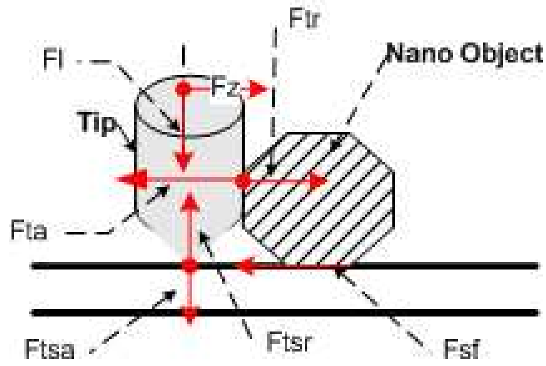

Fig. 2. Tip – nano object – stage model.

It is easy to give a prove that the adhesive forces between the probe tip and stage and between the probe tip and the nano object so and between the nano object and the stage (*Ftsa*, *Fta*, *Fna*) are depends on the area of the nano object and the tip (*Ans*, *Ats*, *Atn*) [2]:

$$\frac{F_{na}}{F_{tsa}} = \frac{A_{ns}}{A_{ts}}\,, \quad (3)$$

$$\frac{F_{ta}}{F_{tsa}} = \frac{A_{tn}}{A_{ts}}\,. \quad (4)$$

3. STRATEGY IN NANO MANIPULATIONS

We may assume that motions into the nano world are similar to the motions into the macro world, but fine path planning of movement and sequence of actions are critical into the nano environment. Movement and operation in nano world are difficult reversible, it means that it is difficult to reach the nano object to operate with him and then release him from the needle or the gripper. The adhesive force between the needle and nano object has to be neglected small compared with the forces of adhesion between particle and surface and the gravity force. It means that exactly choosing of the angle at which the tool approaches the cell, and exact define the way in which the operator will move through the joystick with force feedback. During this motion the operator should be able to around all obstacles in the nano environment - dust, organic particles or other cells that are not objects of examination at the moment.

To perform correctly and safely obtain the desired nano-object and injecting it must perform the following steps:

Display calibration – software should take the dimensions of the particular working stage in order to determine the starting position of the probe tip and the permissible scope of operation.

Object recognition – as mentioned above the operation stage in nano world may not be enough sterile, so it has to be determinate which sites are useful and which sites are targeted by the operator and which of them are not useful from the microscope picture. This step can be done by several different manners. By predefining the criteria for target objects in the software we can apply any of the algorithms for pattern recognition and thus be useful in separating useful and none useful objects. It is not very accurate method and it is straight depends on the

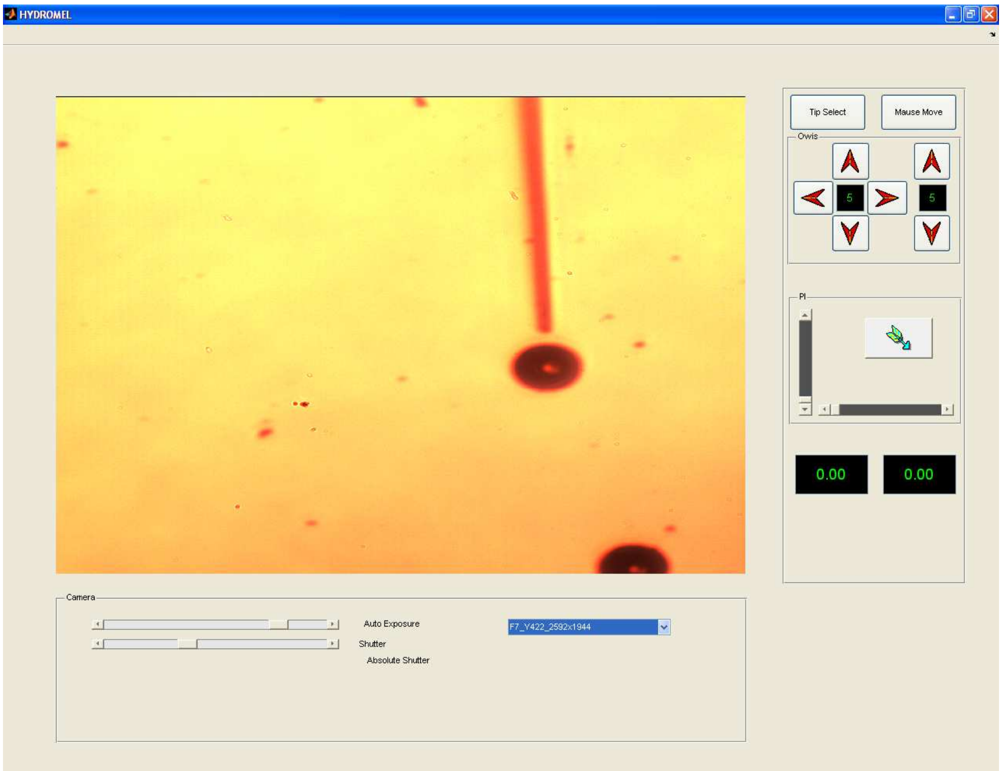

Fig. 3. Hydro-MiNa control panel with objects and obstacle points.

quality of the microscope picture and it is straight depends on the exactly definitions of the target object criteria [7].

The scenario of the Hydro-Mina Robot control panel with the glass pipette and some micro object are shown on Fig. 3.

The large black circles are the target objects. All other smaller sports are the obstacle points which operator has to avoid during the operation with robot. Object recognition for objects in the Fig. 3 may be realized as optical contrast between the objects and the environment. As we can see, target objects are more dramatic painted and has more depth color than all other objects. It can be used in order to determine the borders of the target objects – these are the points where there are major differences of color depth between pixel regions.

Control panel lets operator to move the probe tip on the left-right or up-down directions by clicking particular buttons. Also it allows the view point on the stage to be changed so that picture can be moved to four directions. The probe tip can rich the first object without troubles but to rich the second one is more difficult. It is true because there are some obstacles between two objects. Using discrete movement of the tip (step by step and each step has exact direction according the X, Y axes) it is very important to select the correct path.

Path Planning – during this stage we have to do path planning from the starting position of the probe tip to the target object with some of the motion planning trajectory algorithms. This is one of the most important steps. The main purpose is to prepare the environment as if the probe tip will reach the target automatically by itself. When the operator begin movement to the object if the motion diverts away from the pre-calculated trajectory the human interface device force feedback will stop it.

So the operator role is become like the role of the motorman of the train – controlling and motion support.

When the manipulation over the target nano object has be done, the probe tip will move to the next object by the same algorithm.

4. PATH PLANNING

The goal of path planning task is to generate a set of paths for nano objects reaching while the rules of the maximal distance to the objects which are potential obstacles of the research in order to avoid collisions and other adhesive forces caused by nano mechanical characteristics of the objects. A collision appears when the particles are arranged into the nano environment that restraint circles intersect or touch.

The method that we are applied consist several steps. Pre-recognized studied objects and obstacle objects are enclosed with virtual circles. The center of each circle is the particular object. The radii of circles are the limit of adhesive forces for the particular nano object. The radius of these circles should be large enough so that they ignore the adhesive forces between nano objects and small enough not to cause collisions or intersection of two or more protected areas. These are the limits of movement tractors must cross. One of the important tasks during this stage is to evaluate the vector and the value of adhesive forces for each nano object into the environment. To do it should be used an Atomic Forces Microscope (ATM) or other visual interface with force feedback [8]. Other method for adhesive forces evaluation is based on the potential area of interaction between objects and its nano mechanical models [9].

Now we have to determine our targets. It may be done by operator actions for example by mouse clicking on the virtual objects and remember the coordinates and

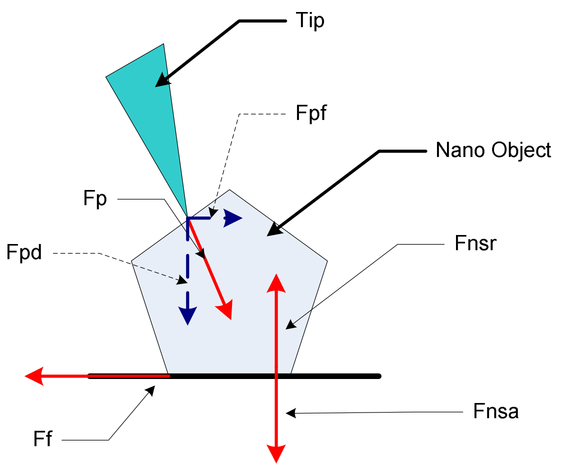

Fig. 4. Cell injection forces.

sequence of each chosen nano object. This step will optimize the follow steps of path planning because we are not interested in all possible paths between objects but we are interested in the paths to the targets only.

Because the main goal of the project is to penetrate the cell membrane without object destruction, the target selection is not only object selection but also the point of injection and the angle of injection that are very important components. As it is shown on the Fig. 4, the angle of injections is very important.

The needle has to get over the surface forces pressured of the cell summarized with force of friction and adhesion forces. So if the injection angle is not correct it couldn't be done. The point of injection is as important as the angle. Because the target objects aren't in regular shapes the exact point of injection should be discovered and chosen. This is very difficult task for the operator, so he/she only points the object by the computer simulator has to compute the exact pint of dipping and needle position in line of the particular object shape. This task is depends on information received from force feedback visual device (ATM) and 3D generated model of the objects.

Next we generate Voronoi diagrams for all objects at the stage. Using this diagram and graph theory algorithm we generate all available paths from the start position to each of the target objects. The probe tube will pass through the optimal path between pre-generated circles.

The second step is to choose the optimal path to the first target nano object. For this purpose we are using the "A Star" algorithm for optimal path choosing. There are a lot of algorithms for this but the used one is one of the most perform and quick one. The evaluated paths show itself on the computer display like fat lines as parts of Voronoi's diagram.

The operator motion simulation is the next stage. During this stage the operator does not do anything. This is a virtual computer simulation of his/her action in order to determine if some collisions appear at the nano environment. A virtual probe tube passes through the generated paths and sequence visits all target objects. The goal is to be discovered eventual collisions which may occur before begin the real actions.

If some collisions are discovered there are several approaches. The first and the most intuitive approach are to regenerate a new Voronoi's diagram with new potential paths. Next start the simulation again until there are no collisions on the stage.

The second approach is to use the same diagram but to use other no so optimal path for target reaching. It is more useful approach because the generation of Voronoi diagram is harder and no so optimal decision. Also building of diagram uses optimal algorithms and it is more rarely to generate different one.

The third approach is to reorder the nano objects at the stage in order to free the paths. This is the most difficult method and there are a lot of recalculations within it. We have to discover the optimal paths of movement and optimal sequence of actions, so that their physical touching to be avoided. As we discussed at the part of nano mechanical force interactions model, because of the big adhesive forces if two or more nano objects stay so near by each other that adhesive forces interactions become bigger than frictional forces and repulsive forces of interaction between object and stage, they will stick one by other. The mechanical and quality characteristics of the researched object would be changed in this situation. It wouldn't be done.

After successfully simulation test done, it comes the moment of real operator actions.

We couldn't rely absolutely of the force feedback during the real operator motion through the generated paths. They should keep the probe tip at the path but there is mechanical moment at the human machine interface and it should be compensated into the nano world. There are lots of compensation algorithms but each of them has definitely acceptable error level. The value of this error level must be absolutely minimized.

One of the possible decisions of the current problem is to be modeled virtual repulse forces around the objects into the software model of the stage. These forces are in sphere shapes and the potential obstacle particles are in the center of these shapes (Fig. 5).

As is shown in the picture above the blue circles are mentioned virtual forces. Red shapes are the potential obstacles which are defined manually from the operator. When the probe tip begins its movement across the surface blue spheres keeps it away from the objects.

The shape of these forces is most similar than sphere form and center is the particular particle. The virtual repulse forces are generated by the formula below [3]:

$$P(d) = \frac{1}{2}\lambda\left(\frac{1}{d} - \frac{1}{d_0}\right),\ d \le d_0,$$
$$P(d) = 0\,,\ d > d_0\,, \qquad (5)$$

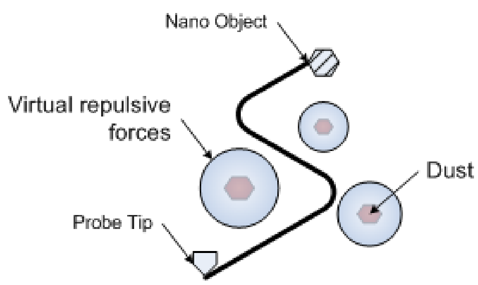

Fig. 5. Virtual repulsive forces.

where:

- d – distance to the particle;
- d_0 – a positive constant which represents the action distance of the potential;
- λ – a position scaling factor.

The vector of virtual repulsive force is defined as negative gradient of the function:

$$\vec{F}_{(d)} = -\nabla P_{(d)} . \tag{6}$$

5. VORONOI'S DIAGRAMS

Let's have a set space S and any number of points Q. Voronoi diagram is such a division of space S, that each piece subspace has exactly one point of the set Q [6].

An example of Voronoi's diagram is shown in Fig. 6. The objects are marked as black points and the borders between particular surfaces are black lines around the points. Each point is at the same destination from the border as the neighbor point from the other side of the border. This is one of the most important characteristic of the Voronoi's diagram.

Two half-planes of the Voronoi have common border. Different Voronoi regions are disjoint. The common boundary is called Voronoi Edge if it contains more than one point [6]. Two points in two different regions with common border are at the same distance from this order.

One of the most performance and optimal algorithms for Voronoi generation diagram V(s) of set of points is named "Divide and Conquer" [6]. The essential part of this algorithm is to generate a vector tat separate a set of points into two different subsets V(L) and V(R) as shown in Fig. 7. The count of points in each of this subset is similar. The next step is to separate each of subsets into two different subsets and using this recourse algorithm to separate all the initial set of points on one-point subsets. It defines a Voronoi's diagram.

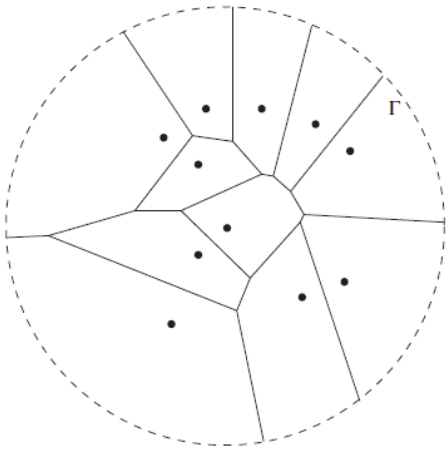

Fig. 6. A Voronoi diagram.

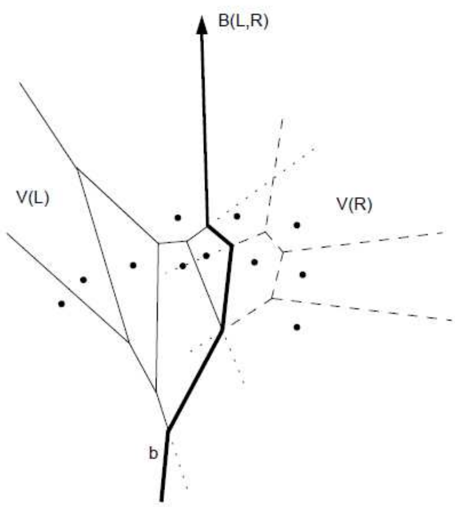

Fig. 7. Split V(s) into V(L) and V(R).

6. ASTAR ALGORITHM

Navigating a terrain and finding the shortest path to a Goal location is one of the fundamental problems in path planning [10]. There are a lot of algorithms which solve this problem but the AStar algorithm is one of the most used ant one of the post optimal one.

We show one of its implementation in Fig. 8.

Let's have a stage with a goal – read circle in Fig. 9 and operator (the blue square). The operator has to reach to the red object passing the optimal path. The black spots are obstacles and the operator hasn't step over them. The stage is separated into squares and we are computing the nearest distance to the goal at each next step. The operator goes to the square that is nearest to this distance.

The movement of the operator to B4 point hasn't situation in which we have to do any choice. There are two possible paths from B4 point. Now we compute the distance to the goal and evaluate the smallest values so the shortest distance. It is through the C3 cell in our situation.

Using the current algorithm with the shown in Fig. 10 scheme we will reach to the D1 cell on the first computing time. But it isn't possible to reach the goal through this cell. It is so called a "dead end" situation. Now we come one step back and do new computing to determine a new cell which is nearest to the goal. The previous cell we mark as locked.

Also we found that the correct path is: A1→A1→B3→C4→D3.

We have done on optimization of the current algorithm. We present the stage as a tree. The root of that tree is the operator – this is a starting point. Each cell is a node of the tree. Each node has a weight parameter which is the distance between particular node and the goal. Beginning with reverse computing – from the goal to the start position we evaluate weights of all cells. The

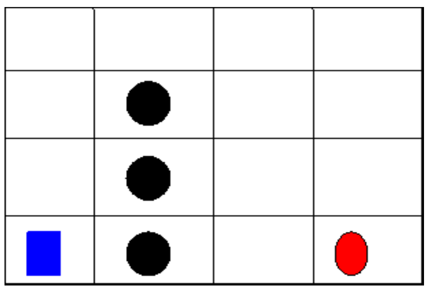

Fig. 8. A Star algorithm start point.

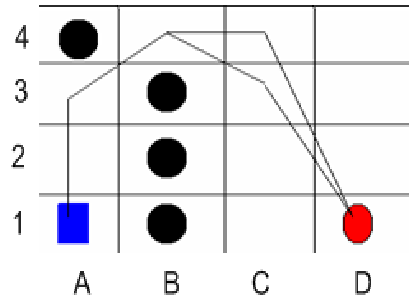

Fig. 9. A Star algorithm paths.

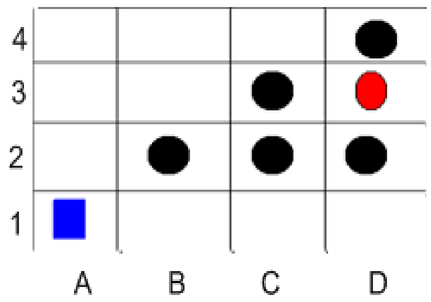

Fig. 10. Dead End.

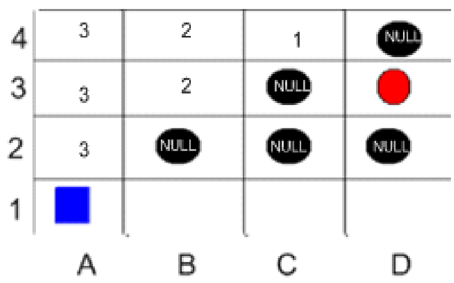

Fig. 11. Weighted Stage.

cells with obstacles are evaluated as NULL. So we have a weighted tree. Now the path finding procedure is faster.

The graphical visualization is shown in Fig. 11. The blue square has to rich the red circle without passing fields with black ellipses (obstacles). We have to weight each field from the object to the tip. All fields around the object are estimated as 1 except where there are obstacles. These fields are estimated with *NULL*. We go through all fields by recursive algorithm and estimate each its neighbor by adding 1 to the certain value. If there are black sphere (obstacle) the field is estimated with *NULL*. The final picture is shown in Fig. 11.

Now the back path (from the tip to the object) is easy to be determined by choosing the smallest neighbor of the current field.

The very important point is that at the first moment all fields have to be initialized as blank (*NULL*) values. In this way we marked the potential paths which are finished with obstacle as impassable (A1→B1→C1→D1).

7. CONCLUSIONS

The combination of Voronoi's diagram and AStar algorithm for path planning to the goal lets us to construct an optimal plan to lead the operator thorough the nano environment. Using existing experience we developed the algorithm of path planning and involve it into the process of operating in nano environment.

In this paper we show some problems during nano environment operations but it does not touch upon the 3D presentation of the stage. The third dimension affects used algorithms and approaches. There are different means of third dimension compensation (Z-Compensation), but this is the goal of our next tasks. The software simulation of the Virtual Environment of the stage is one of the future challenges.

ACKNOWLEDGEMENTS: The authors gratefully acknowledge the partially support of the project SpeCy-MiNT project funded by Bulgarian Science Fund under the Contract Nr. DO 0171/16.12.2008.

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