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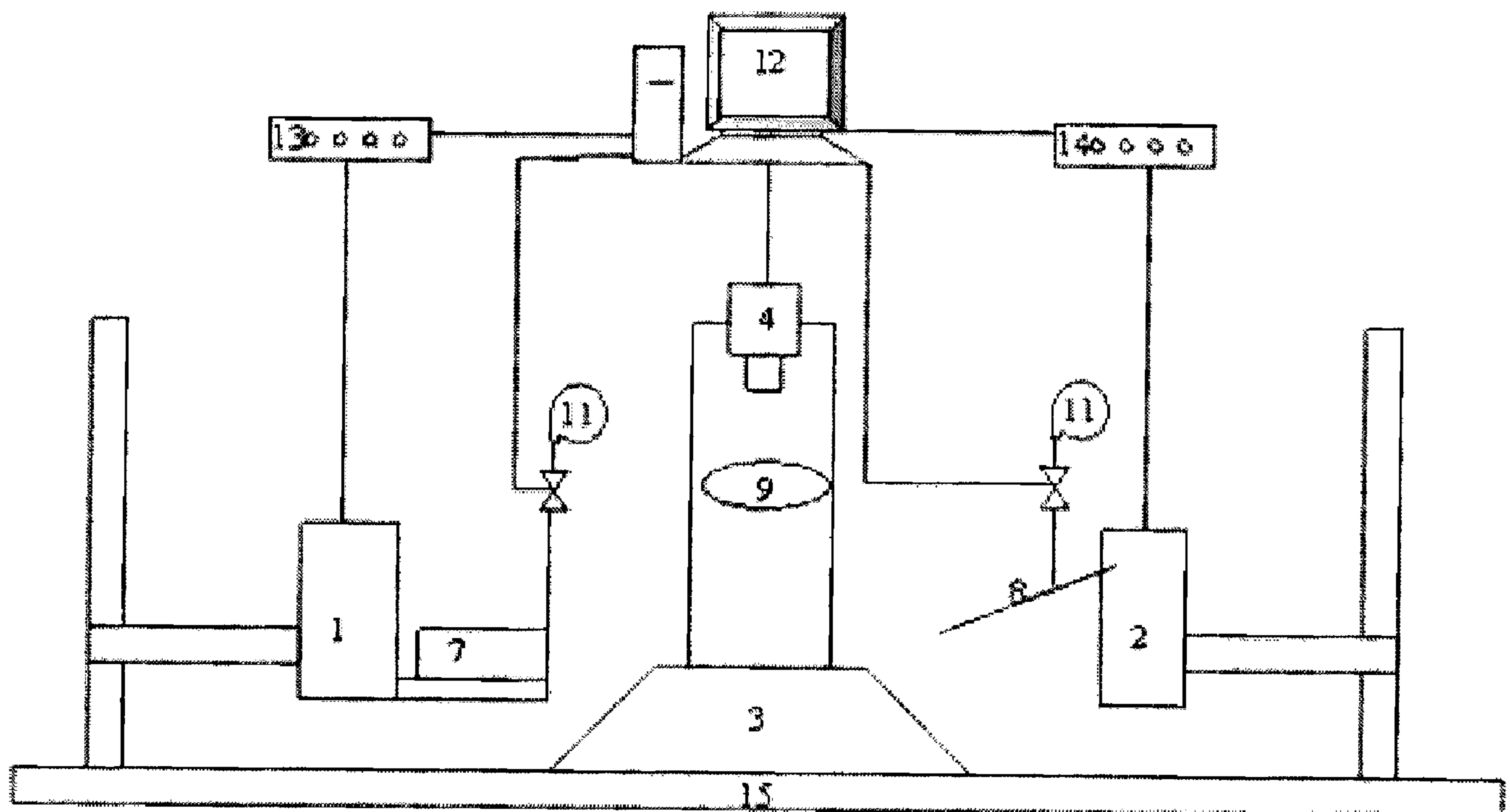
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(54) Titre : SYSTÈME ET METHODE D'INJECTION AUTOMATIQUE A HAUT RENDEMENT DE CELLULES

(54) Title: HIGH-THROUGHPUT AUTOMATED CELLULAR INJECTION SYSTEM AND METHOD



(57) Abrégé/Abstract:

A fully automated cell injection system and method are described, which can perform automatic, reliable, and high-throughput cell injection of foreign genetic materials, proteins, and other compounds. The system and method overcome the problems inherent in traditional manual injection that is characterized by poor reproducibility, human fatigue, and low throughput. The present invention is particularly suited for zebrafish embryo injection but can be readily extended to other biological injection applications such as mouse embryo, drosophila embryo, and *C. elegans* injections, capable of facilitating high-throughput genetic research at both academic and industry levels.



Abstract

A fully automated cell injection system and method are described, which can perform automatic, reliable, and high-throughput cell injection of foreign genetic materials, proteins, and other compounds. The system and method overcome the problems inherent in traditional manual
5 injection that is characterized by poor reproducibility, human fatigue, and low throughput. The present invention is particularly suited for zebrafish embryo injection but can be readily extended to other biological injection applications such as mouse embryo, *drosophila* embryo, and *C. elegans* injections, capable of facilitating high-throughput genetic research at both academic and industry levels.

HIGH-THROUGHPUT AUTOMATED CELLULAR INJECTION SYSTEM AND METHOD

Field of the Invention

5 The present invention relates to cell manipulation, automation, micromanipulation and microrobotics.

Background of the Invention

Recent advances in molecular biology, such as the creation of transgenic organisms, demonstrate
10 that increasingly complex micromanipulation strategies are required for manipulating individual biological cells. In order to create transgenic organisms such as those for cancer studies, genetic materials need to be injected into cells. Conventionally, cell injection has been conducted manually; however, long training, low throughput, and low success rates from poor reproducibility in manual operations call for the elimination of direct human involvement and
15 fully automated injection systems.

The zebrafish has emerged as an important model organism for development and genetic studies, due to the similarities in gene structures to the human being, external fertilization and development, short development period, and the transparency of embryos making it easy to observe the fate of individual cells during development. The recent growth in the number of
20 laboratories and companies using zebrafish in vertebrate developmental genetics has been exponential. The injection of thousands of zebrafish embryos is required on a daily basis in a moderate-sized zebrafish genetics laboratory/company, for applications such as embryonic development studies and mutation screening to identify genes. The laborious manual injection task easily causes fatigue in injection technicians and hinders performance consistency and
25 success rates. The current manual technology is not capable of meeting the needs of such high-throughput applications.

Currently, no automated, high-throughput zebrafish embryo injection systems are available. Many attempts have been made to leverage existing technologies, such as microrobotics and MEMS (microelectromechanical systems), to facilitate the process of cell injection. Microrobot-assisted (i.e. teleoperated) cell injection systems have been developed, where
5 microrobots/micromanipulators are controlled by the operator to provide “steady hand” and conduct “human-in-loop” cell injections. (See R. Kumar, A. Kapoor, and R.H. Taylor, “Preliminary experiments in robot/human cooperative microinjection,” Proc. IEEE International Conf. on Intelligent Robots and Systems, pp. 3186-3191, Las Vegas, 2003; and H. Matsuoka, T. Komazaki, Y. Mukai, M. Shibusawa, H. Akane, A. Chaki, N. Uetake, and M. Saito, “High
10 throughput easy microinjection with a single-cell manipulation supporting robot,” *J. of Biotechnology*, Vol. 116, pp. 185-194, 2005.) Although the microrobots can to a certain extent facilitate cell injection by a human operator without long training, the human involvement still exists in the process of cell injection, resulting in a low throughput and reproducibility.

A visually servoed microrobotic mouse embryo injection system has been developed, using a
15 holding micropipette for immobilizing a single mouse embryo, and a visually servoed microrobot for automated cell injection. (See Y. Sun and B.J. Nelson, “Biological cell injection using an autonomous microrobotic system,” *Int. J. of Robot. Res.*, Vol. 21, pp. 861-868, 2002.) However, switching from one embryo to another was conducted manually, and thus, injection was time consuming.

20 A semi-automated MEMS-based high-throughput *drosophila* embryo injection system was reported recently, where a MEMS microneedle was used as an injector. (See S. Zappe, M. Fish, M.P. Scott, and O. Solgaard, “Automated MEMS-based drosophila embryo injection system for high-throughput RNAi screens,” *Lap Chip*, Vol. 6, pp. 1012-1019, 2006.) A 3-DOF scanning stage was used for locating randomly dispersed embryos that were ‘glued’ on a glass slide, and
25 another 3-DOF motion stage with the injector mounted was employed for injection. One drawback of this system is that manual alignment of the two stages was required before injection. The large alignment error would greatly influence the injection performance. More importantly, the low stiffness of the MEMS injector requires that the hard embryo chorion be removed in order to facilitate the injection, which may affect subsequent embryonic development, making
30 the system unsuitable for zebrafish or mouse embryo injection. Additionally, randomly dispersing embryos slows down the injection speed due to the embryo searching process.

A commercial cell injection system has been developed for oocyte injection of *Xenopus laevis* (frog), where oocytes are manually loaded into a standard 96 well plate, an *x-y* stage is responsible for positioning target cell to the operation area, and a *z*-motor with an injection micropipette mounted conducts cell injection (ROBOOCYTE™ by Multi Channel Systems MCS GmbH). In this system, introducing oocytes into regular patterned wells is conducted manually, which is tedious and time consuming. The injection accuracy was sacrificed due to the open-loop operation. Without feedback, such as vision, integrated into the control system to improve the positioning accuracy and monitor the injection process, the injection performance is sacrificed and robustness not warranted.

U.S. Patent Application No. 20050250197 to Ando et al. discloses a microinjection apparatus and corresponding operation methods. A silicon microfabricated device integrating suction holes is proposed for cell trapping. The deformation of the thin silicon membrane due to an applied suction pressure is compensated for by measuring the height of the membrane with a detection-mark focusing technique. The silicon substrate is not optically transparent, making the observation, monitoring, and control of the injection process difficult.

U.S. Patent Application No. 20050250197 also proposes two methods for measuring the vertical distance between the micropipette tip and substrate surface, using the mirror effects of well-polished silicon surface. The methods intend to determine the height information by focusing on certain features, which will be effective only when the depth of focus is small. However, the size of zebrafish embryos requires a relatively low microscopy magnification that inherently has a large depth of focus (hundreds of micrometers). Thus, the detection methods proposed are not suitable to use for zebrafish embryo injection.

Targeting high-throughput cell injection, MEMS-based microneedle arrays have been developed to perform parallel cell injection. The paper “An array of hollow micro-capillaries for the controlled injection of genetic materials into animal/plant cells” (K. Chun, G. Hashiguchi, H. Toshiyoshi, H. Fujita, Y. Kikuchi, J. Ishikawa, Y. Murakami, and E. Tamiya, in Proc. IEEE Conf. MEMS, 1999, pp. 406–411) describes a microneedle array-based cell injection system, including a microneedle array injector and a microchamber array for cell trapping.

U.S. Patent Nos. 5,262,128 to Leighton et al., 5,457,041 to Ginaven et al., and 6,558,361 to Yeshurun also disclose microneedle array designs for cell injection use. Although the concept of

using microneedle arrays for parallel cell injection is appealing, solutions to several critical issues do not exist. First, precisely aligning microneedles with regularly positioned cells is difficult. Manual alignment (in-plane or x - y alignment) through microscopic observation from an off-optical-axis angle cannot guarantee a high accuracy. Second, determining the vertical distance (out-of-plane or z) between microneedle tips and cells is difficult. Size differences from one cell to another (e.g., zebrafish embryos can differ by 200-300 μ m) make vertical alignment/positioning impossible. Automation is not an option. Third, particularly for zebrafish embryo injection, the size of zebrafish embryos requires microneedles with a tip length of ~600 μ m and outer diameter of 5-10 μ m throughout the 600 μ m length. The injection needles also must be strong enough without buckling under hundreds of microNewton penetration forces during zebrafish embryo injection. These requirements for microneedles make the selection of MEMS-based solutions inappropriate. In summary, parallel injection with MEMS microneedle arrays is not applicable to zebrafish embryo injection.

It should be understood that despite their relatively large size (~600 μ m and ~1.2mm including chorion), zebrafish embryos have a delicate structure and can be easily damaged. They are also highly deformable, making the automatic manipulation task difficult. Therefore specific difficulties in achieving automated zebrafish embryo injection include: (i) the ability to quickly (i.e. seconds) immobilize a large number of zebrafish embryos into a regular pattern; (ii) the ability to automatically and robustly identify cell structures for vision-based position control (i.e. visual servoing) and account for size differences across embryos; and (iii) the ability to coordinately control two motorized positioning devices to achieve robust, high-speed zebrafish embryo injection.

In view of the foregoing, what is needed is a system and method for cellular injection that overcomes the limitations of the prior art, such that the system and method feature automation, robustness, high-throughput (including sample positioning), high success rates, and high reproducibility.

Summary of the Invention

In one aspect, the present invention is a system for automated cellular injection comprising: a first positioner control device operable to control motion of a first positioner, the first positioner connected to a holding device operable to immobilize one or more cells in a desired position, the one or more cells including a target cell; a second positioner control device operable to control motion of a second positioner, the second positioner connected to a micropipette, the micropipette having a tip; a pressure unit connected to the micropipette, the pressure unit operable to pass a desired deposition volume of a material at a desired injection pressure to the micropipette; and a microscope means for viewing the position of the micropipette relative to the holding device; wherein the first positioner control device, the second positioner control device, the pressure unit and the microscope means are linked to a host computer, the host computer including control software for motion control and image processing that enables a user to inject the material into the target cell through the tip of the micropipette.

In another aspect, the present invention is a method for automated cellular injections comprising immobilization, control sequence, and computer vision recognition. According to this method, a number of cells are positioned on a holding device and viewed through a microscope means. Each cell is recognized and centered in the field of view, and the micropipette tip is moved to a "switching point" for the target cell, as defined herein. The tip penetrates the chorion of the target cell and deposits material into the cytoplasm of the target cell. The next cell is then brought into the field of view. The cell is recognized, and injection process is repeated until all cells in the batch are injected.

In yet another aspect, the present invention provides a contact detection method to establish a home position for the micropipette in order to avoid unwanted contact between the micropipette tip and the cells when shifting between cells in the injection order. Upon retraction from the cell, the tip is moved to the home position.

The present invention allows for precise, highly reproducible deposition of foreign materials into a cell or a yolk of an embryo. Although the present description discusses depositing material into the cytoplasm center for embryos, it should be understood that the present invention is readily adaptable to allow for the deposition of material into other parts of a cell or embryo, as desired.

The present invention overcomes the problems of poor reproducibility, human fatigue, and low throughput inherent with traditional manual injection techniques. Besides automating cell injection by replacing human operation with high reliability and success rates, the present invention also provides high reproducibility and enables genuine high-throughput genetic research. The system and method have been implemented for the injection of zebrafish embryos, but can be readily extended to automated injection of other biological entities, such as mouse embryos, *drosophila* embryos, and *C. elegans*.

Brief Description of the Drawings

A detailed description of the preferred embodiments is provided herein below by way of example only and with reference to the following drawings, in which:

Figure 1 illustrates a schematic diagram of components of the high-throughput automated cellular injection system.

Figures 2(a)-(d) illustrate schematic diagrams of a zebrafish embryo holding device from a top view, bottom view, A-A section view and B-B section view, respectively.

Figure 3 illustrates coordinate frames in the present invention.

Figure 4 illustrates an image projection model relating camera/image frames.

Figures 5(a)-(h) illustrate micropipette motion sequences for injecting each embryo.

Figures 6(a)-(e) illustrate embryo injection sequences and through-hole configuration.

Figure 7 illustrates automatic injection control flow.

Figure 8 illustrates a micropipette moving in the image plane.

Figure 9 illustrates contact between micropipette tip and embryo holding device.

Figures 10(a)-(e) illustrate image processing steps for embryo structure recognition.

Figure 11 illustrates convexity defects between the cell contour and its convex hull.

Figure 12 illustrates parallel task execution of the two positioners.

Figure 13 illustrates alternative injection control flow with an on-line pixel size calibration step.

Figure 14 illustrates an example control program interface.

5 In the drawings, one embodiment of the invention is illustrated by way of example. It is to be expressly understood that the description and drawings are only for the purpose of illustration and as an aid to understanding, and are not intended as a definition of the limits of the invention.

Detailed Description of the Invention

10 With reference to Figure 1, a system in accordance with the present invention comprises the following main components:

- (i) Two motorized positioning devices (herein termed 'positioner') 1, 2, such as multi-DOF motorized positioning stages or microrobots/micromanipulators that control the motion of embryos and micropipette 8, respectively.
- (ii) 15 Control software unit running on a host computer 12 for motion control and image processing.
- (iii) Positioner control device 13, 14 connected to or mounted on the host computer 12 to physically provide control signals to the two positioners 1, 2 and the pressure unit 11 (component viii).
- (iv) An embryo holding device 7 placed on one positioner 1.
- 20 (v) An injection micropipette 8 (glass capillary or microfabricated needle) attached to the second positioner 2. The tip of the micropipette 8 is ~600µm long and within 10µm in outer diameter throughout the length of 600µm, as an example.
- (vi) An optical microscope (objective 9 and base 3).
- (vii) A CCD/CMOS camera 4 mounted on the optical microscope.

(viii) A computer-controlled pressure unit **11**.

(ix) A vibration isolation table **15** to minimize vibration (optional).

Although this particular configuration of the system relates to the injection of material into zebrafish embryos, it should be expressly understood that this is an illustrative example only and the present invention is readily adaptable for the automated injection of other biological entities such as mouse embryos, *drosophila* embryos, and *C. elegans*, or any other appropriate cell as would be recognized and understood by a person of skill in the art. As would be appreciated by a person of skill in the art, the precise techniques of cell immobilization and cell structure would vary for different biological entities.

10 An embryo holding device **7**, either microfabricated or conventionally machined, is used to position a large number of zebrafish embryos into regular patterns. Figure 2 shows one example vacuum-based device. The device described in Figure 2 has two parts: embryo sucking structure **20**, a flat piece **200** glued on the bottom of the embryo sucking structure **20**. Arrays of through holes **201** are used to immobilize zebrafish embryos with negative pressure applied through the
15 air outlet **202** on the side wall of the chamber **205**. When a large number of zebrafish embryos are dispersed onto the device, each hole immobilizes a single embryo, and the non-trapped embryos are flushed away. Materials to use for constructing the cell holding device are ideally optically transparent, biocompatible, and easy for machining (e.g., polycarbonate).

The diameter of the through holes **201** is between 0.4mm and 0.5mm, for example. This through
20 hole size is particularly suitable for zebrafish embryos. For mouse embryos, for example, the hole diameter would be smaller, about 20-40µm, for example. Preferably, the negative pressure applied to immobilizing embryos should be low enough not to cause damage or negative effects for embryonic development. For example, the negative pressure is 0.5-7.5InHg.

A reservoir **204** contains culture media/solution throughout the injection process. A slope **210**
25 on the bottom surface of the holes **201** can be created in order for air bubbles to escape more readily such that they do not stick to the bottom surface. The three airflow channels **208** along the bottom surface are for inducing air to smoothly flow out of the chamber **205** via the air outlet **202**. The air outlet **202** is positioned higher than the slope **210** to guarantee that the slope **210** is

submerged in culture media/solution. The steps 209 are created such that the cell holding device can be fixed by two clamps under the microscope.

The coordinate frames of the system used in Figure 3 and Figure 4 are summarized in Table 1.

Symbol	Coordinate frame
e	End-effector coordinate frame $X_e-Y_e-Z_e$ attached to positioner 2 (micropipette 8 as the end-effector)
t	Target coordinate frame $X_t-Y_t-Z_t$ attached to positioner 1 that controls the motion of embryos
c	Camera coordinate frame $X_c-Y_c-Z_c$
i	Coordinate frame x_i-y_i (or $x-y$) for the image plane

Table 1. Coordinate frames (Figure 3 and Figure 4) of the system.

- 5 A point $P=(x,y,z)$ in the camera frame $X_c-Y_c-Z_c$ is mapped to a point $p=(u,v)$ in the image plane $x-y$ via

$$\begin{bmatrix} s_x & 0 \\ 0 & s_y \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} x \\ y \end{bmatrix}$$

where s_x and s_y are fixed scale factors or pixel size in x -axis (s_x) and y -axis (s_y) respectively that can be either calibrated off-line manually or on-line automatically as discussed later. They will
10 be referred to as s thereafter.

Overall injection method

A large number of zebrafish embryos are first positioned in a regular pattern on the embryo holding device 7. The embryos are brought into focus with an auto-focusing algorithm. A vision-based contact detection algorithm determines the vertical positions of the micropipette tip and the top surface of the holding device 7. Each embryo is recognized and centered in the field
15 of view; simultaneously, the micropipette tip is moved to a switching point. The tip penetrates the chorion 51 and deposits genetic materials into the cytoplasm 52 of the target cell. Upon retreating out of the embryo, the tip is moved to the home position. In the meanwhile, the next embryo is brought into the field of view. The embryo is recognized, and injection process is
20 repeated until all embryos in the batch are injected.

Micropipette motion control sequence for injecting each embryo

‘Cytoplasm’ in this invention refers to the combination of the yolk and the cells of an embryo, e.g., a zebrafish embryo. As shown in Figures 5(a)-(d), when the micropipette tip is nearly horizontal, the two principal planes **53** and **54** (crossing the cytoplasm center **O**, parallel to the X_e - Z_e and X_e - Y_e plane, respectively) overlap at two points. The point that is closer to micropipette **8** is referred to as the switching point **S**. The motion sequence of the micropipette **8** for injecting one embryo is as follows:

1. Move from home position (home position, described later in control flow **702** and **703**, is above and to the right of the chorion **51**) to the switching point **S** simultaneously along all three axes with positioner **2** (Figure 5(b)). In the meanwhile, the embryo cytoplasm center **O** is brought to the center of the field of view by positioner **1**.
2. Penetrate the chorion **51** and move to the cytoplasm center **O** along the X_e direction only (Figure 5(c)). Upon reaching center **O**, a pre-specified amount of genetic materials (e.g., DNA or morpholinos) is deposited by the computer-controlled pressure unit **11**.
3. Retreat from the cytoplasm center **O** beyond the switching point **S** along the X_e direction only (Figure 5(d)).
4. Move to home position (Figure 5(a)). Simultaneously, the next embryo is brought into the field of view by positioner **1**.

This invention allows for precise, highly reproducible deposition of foreign materials into the cell or the yolk. The following description assumes that one desires to deposit foreign materials into the cytoplasm center for every embryo.

When the micropipette tip has a significant tilting angle (e.g., $>5^\circ$) as shown in Figure 5(e)-(h), micropipette motion control sequence can be made slightly different from the above-mentioned in order to minimize cellular damage. The two different steps are: (i) principal plane **54** still crosses cytoplasm center **O** but is parallel to micropipette tip **8** from the side view; and (ii) during penetration and retraction, the micropipette moves along the direction of its principle axes (Figure 5 (g)-(h)), instead of purely along the X_e direction.

Although the following description corresponds to the case shown in Figure 5(a)-(d), the invention can also be implemented as shown in Figure 5(e)-(h).

Injection path planning

Denote the pitch (i.e., spacing between two adjacent holes **201**) along the X_t and Y_t directions as Δx and Δy . Denote the number of embryos along the X_t and Y_t directions as m and n . Starting with the first embryo (Figure 6(a)-(d)), positioner **1** is controlled to travel along the path shown in dashed lines for sequential injection of the entire batch of embryos. Of the four paths when embryos are arranged in regular grids (most often $m > 2$, $n > 2$), given $\Delta y > \Delta x$, path **61** shown in Figure 6(a) is the shortest. Given $\Delta x > \Delta y$, path **62** shown in Figure 6(b) is the shortest. In the case of $\Delta y = \Delta x$, the four paths have the same total travel distance. In order to increase throughput, the shortest path should be taken.

The through holes **201** can also be arranged into other patterns other than those shown in Figure 6(a)-(d). For example, every six nearest holes **201** to the middle one can be such configured that they form an equilateral hexagon (Figure 6(e)). Such a configuration achieves a maximum number of holes for a given device surface area, which can be adopted for the purpose of maximizing the number of embryos for each batch.

Injection control flow

After a batch of zebrafish embryos are immobilized on the cell holding device **7**, fully automated operation starts according to the control flow as described in Figure 7.

20 Embryo auto-focusing **701**:

Prior to autonomous injection, the embryos need to be brought into focus. This auto-focusing step **701** only needs to be conducted once for each batch of embryos. Embryos are servoed by positioner **1** upwards (or downwards) by a certain distance (e.g., 5mm) to cross the focal plane. An autofocus algorithm (e.g., Tenenbaum gradient) is used to locate the focal plane by constantly calculating the focus measure for each frame of image. The embryos are moved to the focal plane that corresponds to the maximum (or minimum) focus measure.

Identification of micropipette tip ROI (region of interest) 702:

This step is to locate the tip of the micropipette **8** for use in contact detection **703**. The micropipette **8** controlled by positioner **2** moves only along the Y_e direction. The moving micropipette that stands out in the image subtracted from the background is recognized (i.e., a region of interest **81** around the tip of the micropipette, shown in Figure 8 is identified). Upon identification, the coordinates of the tip both in the image plane $x-y$ and in the end-effector frame $X_e-Y_e-Z_e$ are determined. The x -coordinate and y -coordinate in the image plane $x-y$, X_e -coordinate and Y_e -coordinate in the end-effector frame $X_e-Y_e-Z_e$ are taken as the lateral components of the home position of the micropipette tip.

Contact detection 703 using computer vision feedback:

This step is to automatically align the tip of the micropipette **8** with the embryo cytoplasm center **O** in the vertical direction. In this procedure, the top surface of the cell holding device **7** serves as the reference plane. The micropipette **8** moves only along the Z_e direction. Upon the establishment of the contact between the micropipette tip and the top surface, further vertical motion of the micropipette tip along the Z_e direction results in lateral movement along the X_e direction. As shown in Figure 9, the micropipette tip is located at point **a** (initial contact) and **b** (after contact) in the surface plane. Before and after contact, the micropipette tip changes its x coordinate in the image plane $x-y$ vs. time (i.e., image frame number), resulting in a V-shaped curve. The peak of the V-shaped curve represents the contact position along the vertical direction between the micropipette tip and the top surface of device **7**.

After contact detection, the Z_e -coordinate of the switching point **S** is determined by moving upwards with respect to the contact position by half of the embryo diameter, e.g., 0.5-0.6mm. The Z_e -coordinate of the home position of the micropipette tip is determined by moving upwards with respect to the contact position by the embryo diameter, e.g., 1.0-1.2mm.

Upon the completion of **702** and **703**, the home position of the micropipette tip both in the $x-y$ image plane and the $X_e-Y_e-Z_e$ frame has been automatically determined and will be fixed for use in the following procedures of injecting all embryos within the batch.

Moving to the home position 704:

After **702** and **703**, positioner **2** following a position control law (e.g., PID) moves the micropipette tip upwards and laterally to its home position determined in **702** and **703** from the vertical contact position in order to prevent the micropipette from crashing with embryos in
 5 between injections.

Embryo recognition 705:

The objectives of this step are to identify the cytoplasm center **O** (Figure 10(a)), the distance from the center **O** to the switching point **S** along the **x** direction, and the injection angle γ between the **x** axis and the principal axis **104** (Figure 10 (e)).

10 The embryo recognition steps are summarized in Table 2. The complete recognition process typically takes 16ms on a PC (3.0GHz CPU and 1GB memory).

Step #	Processing
1	Pre-processing
2	Chorion 51 recognition
3	Cytoplasm 52 recognition
4	Determination of injection angle γ

Table 2. Embryo recognition **705**.

(1) Pre-processing. This step is to obtain a de-noised binary image. The image is first convolved with a low-pass Gaussian filter for noise suppression. Then the gray-level image is
 15 binarized to a black-white image using an adaptive thresholding method (e.g., setting a local threshold for each pixel as the mean value of its local neighbours). The binary image is eroded to remove small areas that are not of interest and then, dilated to connect broken segments that originally belong to one object. An example image after pre-processing is shown in Figure 10(b).

20 (2) Chorion **51** recognition. Of many connected objects in the binary image, the one with the maximum area is taken as the chorion **51**. In Figure 10(c), the chorion **51** is circumvented by its minimum enclosing circle **101**.

(3) Cytoplasm **52** recognition. The second largest object in the image shown in Figure 10(b) is the cytoplasm **52**. Its boundary is represented by a chain code contour. In some cases, the boundary of the cytoplasm **52** is not fully connected (i.e., a rotated 'C' shape with an opening other than a fully closed 'O' shape). Thus, a convex hull of the contour is used for further processing.

A region R is convex if and only if for any two points $x_1, x_2 \in R$, the complete line segment x_1x_2 with end points x_1 and x_2 is inside the region R . The convex hull of a region is the smallest convex region H that satisfies the condition $R \subseteq H$.

The constructed convex hull of the contour serves as the initial curve for 'snakes', which will form a closed curve that represents the contour of cytoplasm **52**. The obtained closed contour **102** by snake tracking is shown in Figure 10(d). The centroid of the contour is recognized as the cytoplasm center O .

The switching point S is then determined as the intersect point of the minimum enclosing circle **101** and the horizontal line passing through the cytoplasm center O , as shown in Figure 10(d).

(4) Determination of injection angle γ . Fitting the contour **102** of the cytoplasm **52** into an ellipse **103** using a least squares method results in the major axis of the fitted ellipse **103**, which is taken as the principal axis **104** (Figure 10(e)).

In order to determine the injection angle γ that represents the cell orientation, the yolk and the cell must be distinguished. The contour **102** is intercepted into two parts (cell part and yolk part) by the minor axis of the fitted ellipse **103**. Define the area difference between a contour and its convex hull as the convexity defect. The convexity defects (Figure 11) for the yolk part and cell part are calculated. Based on the fact that the yolk part always has a much more circular shape than the cell part (i.e., smaller defect), the contour with a greater defect is recognized as the cell part, thus, the cell part and yolk part are recognized. Figure 10(e) shows the principal axis **104** starting from the cytoplasm center O (+) and ending on the cell contour ($\times$). The injection angle γ is the angle between the x axis and the principal axis **104**. As the injection angle γ represents cell orientation, the recognition of γ can also be important for automatically rotating embryos. For example, the angle can be constantly recognized in each frame of image as visual feedback

for rotating an embryo such that the yolk part or the cell part can be rotated closed to or away from the micropipette tip.

The following two tasks **7061** and **7062** are performed in parallel after task **705**.

Centering embryo 7061:

- 5 According to calibrated pixel size s and the distance between the cytoplasm center O and the image center in the image plane, positioner **1** is controlled with a position control law to move the embryo into the image center.

Moving the micropipette tip to switching point 7062:

- 10 In parallel with centering embryo **7061**, the micropipette **8** is then moved by positioner **2** from home position to the switching point S by a position control law (e.g., PID).

Entry into the embryo 707:

The micropipette tip is controlled to start from the switching point S to arrive at the cytoplasm center O by a position control law at an appropriate speed that does not cause embryo lysis.

Genetic material deposition 708:

- 15 Based on a desired deposition volume, the micropipette tip size (inner diameter) and specified injection pressure level determine the positive pressure pulse length (i.e., pressure ‘on’ time). Injection pressure is maintained high for the determined time period through the computer-controlled pressure unit **11**, precisely depositing a desired volume of genetic materials at the cytoplasm center O .

20 Exiting from the embryo 709:

Controlled by positioner **2**, the micropipette **8** is retracted out of the embryo by a position control law at an appropriate speed that does not cause embryo lysis.

The following two tasks **7101** and **7102** are performed in parallel.

Moving the next embryo into the field of view 7101:

This step brings the next embryo into the field of view (the image plane x - y) according to the pitches between adjacent through holes **201** of the embryo holding device **7**. Traveling the relative displacement (Δx or Δy) is executed by an appropriate position control law, driven by
 5 positioner **1**.

Moving micropipette to the home position 7102:

In parallel with bringing the next embryo into the field of view **7101** with positioner **1**, positioner **2** following a position control law moves the micropipette tip upwards and laterally to its home position determined in **702** and **703**.

10 Repeat 705-7061-7062-707-708-709-7101-7102 for each embryo:

In order to achieve the highest throughput, for injecting each embryo, the two positioners **1**, **2** perform tasks in parallel whenever possible, as shown in Figure 12. Performing tasks in parallel operation is an effective approach to enhance the efficiency of the system.

An alternative injection control flow

15 The control flow described in Figure 7 requires a prior knowledge of pixel size s that is obtained through off-line pixel size calibration. The pixel size s varies with different microscopy magnifications that are typically determined by microscope objectives, couplers, and the camera. In order to eliminate the magnification/hardware dependence, on-line calibration can be conducted to automatically determine the pixel size. Accordingly, the control flow is modified
 20 (Figure 13), particularly, for the operation on the first embryo when on-line pixel calibration is conducted.

Comparing the control flow shown in Figure 7 and the flow shown in Figure 13, one can see that **7061** is replaced with task **712**. Also note that **712** is not performed in parallel with **7062**.

Centering embryo, visual servo control 712:

25 Unlike **7061**, **712** visually servos the cytoplasm center **O** to the center of the field of view. The cytoplasm center **O** recognized in step **705** is selected as the image feature for tracking and a

visual tracking method (e.g., sum-squared-difference) is applied. The cytoplasm center O is continuously tracked, providing visual feedback to the image-based visual servo control loop. Based on the visual tracking results (i.e., pixel displacement in the image plane $x-y$) and the position feedback from positioner 1 (i.e., travelling distance in the frame $X_t-Y_t-Z_t$), the pixel size s is calibrated on line.

System robustness enhancement

Error-free operation is critical to warrant the commercial viability of the system. From the perspective of robustness enhancement, the system features an error protection mechanism. Table 3 summarizes potential errors that can occur during operation and their detection methods. When any error is detected, the system is halted with alarms sounded to alert the user and detailed error messages reported to the user.

In control software design that implements the control flow described in Figure 7 or Figure 13, the detection methods must also be implemented as integrative components for system robustness enhancement.

Error description	Detection method
1. Hardware problems: failure in establishing communication with controllers, error in positioner control device, etc.	Query camera, positioner control device, communication channel upon launching the control software.
2. Lighting problem: light off or poor illumination	Calculate the average gray-level and standard deviation of a random frame of image. If the two parameters are both lower than a pre-set threshold value, for example, both are too low, lighting problem most probably exist.
3. Failure in detecting micropipette tip ROI in 702	In most cases, within several frames (e.g., 5-10, depending on the positioner 2 speed and microscopy magnification) the micropipette tip can be detected. If the tip is not detected within 20 frames of images, failure most probably has occurred.
4. Error in contact detection 703	The micropipette tip can be too small a feature to be recognized with a noisy background. If the tip cannot be constantly detected in any frame of image when the tip is being lowered down, an error should have occurred.
5. Embryo recognition error	In each of the following cases, an error is detected: (1) If the radius of the minimum enclosing circle for the chorion is too large, for example, exceeding half of the image width in pixel, or is too little. (2) If the recognized cytoplasm center is outside the minimum enclosing circle. (3) If the recognized cytoplasm center is too close to the chorion. (4) If the fitted ellipse of the cytoplasm contour has a minor axis greater than 2/3 diameter of the minimum enclosing circle.

Error description	Detection method
6. Micropipette tip clogging	After injecting a number of embryos (e.g., a batch of 25), micropipette clogging should be inspected. The pressure unit 11 pushes genetic materials (e.g., DNA) out of the micropipette tip to form a sphere. Based on image processing, if no sphere is formed or a reduced radius is identified compared to the clogging-free case, clogging should have occurred. Alternatively, for each embryo within a batch, negative pressure applied by the pressure unit 11 can be measured constantly (e.g., with a pressure sensor integrated in the pressure path), an abnormal pressure value indicates partial or complete clogging of the micropipette. Using the pressure monitoring approach, micropipette breakage can also be detected.
7. Micropipette buckling	Buckling can occur under one of the following conditions: (1) micropipette tip is misaligned with the embryo; (2) embryo is not fully immobilized; (3) in rare cases, chorion of the embryo is exceptionally stiff and much harder to penetrate. Micropipette buckling can be detected by visually monitoring if the micropipette contour changes from a straight line to a curve pattern.
8. Reaching motion limit of positioners	The first method is to constantly check the position feedback from the positioners. The second method is to monitor overall image changes when the positioners are supposed to move. Little or no image pattern changes indicate that the positioners could have reached limit.
9. On-line calibration error	Before on-line calibration is conducted, if the cytoplasm center of the first embryo is exactly at or extremely close to the image plane center, on-line calibration can result in significant error (divide-by-zero).

Table 3. Potential errors and corresponding detection methods.

The system is capable of automatically inject embryos sequentially for a complete batch. It also allows only injecting selected embryos within a batch. For example, in one user-friendly control interface shown in Figure 14, area **141** provides an interactive means for the user to select embryos from a batch for injection by clicking the circles (circle positions correspond to embryo positions), besides displaying the current operation status (different color indicates completed, on-going, or to be conducted).

It will be appreciated by those skilled in the art that other variations of the preferred embodiment may also be practised without departing from the scope of the invention.

10 The high-throughput automated cellular injection system described herein has at least the following general advantages:

- i) high success rate;
- ii) high reproducibility (because the embryo structure is fully recognized, the deposition target can be selected other than the cytoplasm center **O**);

- iii) high-throughput;
- iv) fast embryo immobilization;
- v) low-cost, biocompatible, optically transparent embryo holding device that produces high image quality for image processing/pattern recognition;
- 5 vi) fully automatic contact detection, facilitating precise alignment of the micropipette tip and embryo center in height;
- vii) optimized embryo injection path to shorten positioners' total travel distance;
- viii) robust image processing methods;
- ix) optical platform (e.g., microscopy magnification) independence, enabled by the on-line
10 pixel size calibration technique;
- x) automated, precise material deposition using a computer controlled pressure unit;
- xi) enhanced robustness due to error detection mechanisms; and
- xii) user-friendly control program interface providing operation flexibility and process monitoring.

What is claimed is:

1. A system for automated cellular injection comprising:

(a) a host computer including control software for motion control and image processing;

5 (b) a first positioner control device operable to control motion of a first positioner, the first positioner connected to a holding device operable to immobilize one or more cells in a desired position, the one or more cells including a target cell;

10 (c) a second positioner control device operable to control motion of a second positioner, the second positioner connected to a micropipette, the micropipette having a sharp tip;

(d) a pressure unit connected to the micropipette, the pressure unit operable to pass a desired deposition volume of a material at a desired injection pressure to the micropipette; and

15 (e) a microscope means for viewing the position of the micropipette relative to the holding device;

wherein the first positioner control device, the second positioner control device, the pressure unit and the microscope means are linked to the host computer; and

wherein the host computer enables the injection of materials into the target cell through the tip of the micropipette.

20 2. The system for automated cellular injection of claim 1 wherein the first positioner and second positioner are selected from a group consisting of multi-DOF motorized positioning stages or motorized micromanipulators.

25 3. The system for automated cellular injection of claim 1 wherein the micropipette is a glass capillary or microfabricated needle having a tip length of about 100-800 μ m and an inner diameter of about 5-10 μ m.

4. The system for automated cellular injection of claim 1 wherein the microscope means comprises an optical microscope linked with a CCD/CMOS camera.
5. The system for automated cellular injection of claim 1 further comprising a vibration isolation table to minimize vibration.
- 5 6. The system for automated cellular injection of claim 1 wherein the one or more cells are embryos.
7. The system for automated cellular injection of claim 6 wherein the embryos are zebrafish embryos.
8. The system for automated cellular injection of claim 1 wherein the holding device is
10 vacuum-based.
9. The system for automated cellular injection of claim 1 wherein the holding device includes a reservoir to contain a solution.
10. The system for automated cellular injection of claim 1 wherein the holding device is made of biocompatible and optically transparent material.
- 15 11. The system for automated cellular injection of claim 1 wherein the holding device comprises through holes with a height greater than about 2-3mm and a diameter of about 0.4-0.5mm, the through holes having a bottom surface, the bottom surface having a tilting slope and airflow channel.
12. The system for automated cellular injection of claim 11 wherein negative air pressure is
20 applied to the one or more cells via the through holes.
13. The system for automated cellular injection of claim 12 wherein the negative air pressure is about 0.5-7.5InHg.
14. The system for automated cellular injection of claim 1 wherein the control software comprises contact detection means.

15. The system for automated cellular injection of claim 1 wherein the one or more cells are injected with the material according to an injection order, and wherein the injection order is optimized such that the total distance of movement of the first positioner is minimized.
- 5 16. The system for automated cellular injection of claim 1 wherein injection of the target cell is achieved via position control means or visual servo control means.
17. The system for automated cellular injection of claim 6 wherein the control software includes image processing means operable for:
 - (a) pre-processing an embryo image to obtain a de-noised image;
 - (b) determining chorion size for the target cell;
 - 10 (c) approximating a cytoplasm center for the target cell;
 - (d) based on the chorion size and cytoplasm center, a switching point for the target cell is determined; and
 - (e) distinguishing a cell and a yolk part according to convexity defects, wherein an injection angle for the micropipette is recognized in substantially real-time.
- 15 18. The system for automated cellular injection of claim 17 wherein the image processing means enable users to select a deposition destination within the target cell.
19. The system for automated cellular injection of claim 17 wherein pixel size can be on-line calibrated with a visual servo control means in order to make the system generally independent of microscopy magnification differences.
- 20 20. The system for automated cellular injection of claim 1 wherein the first positioner and the second positioner are controlled to execute tasks in parallel to increase throughput.
21. The system for automated cellular injection of claim 1 wherein the control software includes error detection means.
22. The system for automated cellular injection of claim 1 wherein the control software
25 includes an interactive control program interface.

23. The system for automated cellular injection of claim 1 wherein the system is capable of automatically injecting cells sequentially for a complete batch or injecting selected cells within a batch.
24. The system for automated cellular injection of claim 1 wherein entry and retraction of the micropipette into the one or more cells is controlled to minimize damage to the one or more cells.
25. The system for automated cellular injection of claim 1 wherein entry is about 1 to 2mm/s and the extraction is about 2 to 3mm/s.
26. A method for automated cell injection comprising:
- (a) placing a plurality of cells on a holding device, the plurality of cells including a target cell;
 - (b) viewing the plurality of cells using a microscope means;
 - (c) positioning the target cell into a desired position using a first positioner, the first positioner controlled through a host computer;
 - (d) moving a micropipette from a home position using a second positioner, the micropipette having a tip, the second positioner controlled through the host computer;
 - (e) the tip penetrating the target cell, wherein the micropipette injects a desired volume of material into the target cell; and
 - (f) moving the micropipette back to the home position.
27. The method for automated cell injection of claim 26, wherein the plurality of cells are a plurality of embryos, and the target cell includes chorion and cytoplasm.
28. The method for automated cell injection of claim 27 wherein the target cell includes a cytoplasm center and the chorion includes a switching point.

29. The method for automated cell injection of claim 28 wherein the tip penetrates the target cell at the switching point and deposits the material at approximately the cytoplasm center.
30. The method for cell injection of claim 26 wherein the micropipette injects the target cell at a desired pressure.
31. A method for the automated injection of embryos comprising:
- (a) placing a batch of embryos on a holding device, the holding device movable by a first positioner;
 - (b) viewing the batch of embryos using a microscope means;
 - (c) using an embryo recognition means to calculate a distance from a cytoplasm center of a target embryo to a switching point on a chorion of the target embryo;
 - (d) moving the holding device to move the target embryo into the center of the image plane;
 - (e) moving a micropipette using a second positioner, the micropipette having a tip, such that the tip penetrates the target embryo at the switching point and deposits a desired amount of material at approximately the cytoplasm center;
 - (f) retracting the tip at a speed that does not cause embryo lysis;
 - (g) moving the holding device to move a next target embryo into the center of the image plane; and
 - (h) repeating steps until all embryos in the batch of embryos have been injected with the material.
32. The method for the automated injection of embryos of claim 31 wherein the embryo recognition means comprises steps of:
- (a) pre-processing to obtain de-noised binary images;

- (b) chorion recognition;
- (c) cytoplasm recognition; and
- (d) determination of the injection angle.

33. The method for the automated injection of embryos of claim 31 further comprising initially establishing a home position for the micropipette by:

- (a) moving the micropipette to recognize its tip;
- (b) further moving the micropipette downwards until contact with a top surface of the holding device is detected;
- (c) raising the tip substantially vertically by a half embryo diameter; and
- (d) determining a home position for the tip based on (a), (b), and (c), such that when the micropipette is in the home position the tip cannot contact the batch of embryos when moving the holding device.

34. The method for the automated injection of embryos of claim 31 wherein a position control means or a visual servo control means is used to move the target embryo into the center of the image plane.

35. The method for the automated injection of embryos of claim 31 wherein the embryo recognition means calculates an injection angle.

36. The method for automated cell injection of claim 26 wherein the cells are zebrafish embryos.

37. The method for the automated injection of embryos of claim 31 wherein the embryos are zebrafish embryos.

38. A vacuum based cell-holding device, the device comprising:

- (a) a structure having a top surface and a bottom surface, the top surface having a reservoir, the reservoir having an array of holes, the array of holes extending from the top surface to the bottom surface, the bottom surface defining a slope; and
- (b) a base connected to the bottom surface, an area between the bottom surface and the base defining a chamber, the chamber having an air outlet;

wherein the air outlet is positioned higher than the slope, and wherein the holes are operable to immobilize cells.

39. The device of claim 38 wherein the bottom surface has airflow channels for inducing air to flow out of the chamber via the air outlet.

10 40. The device of claim 38 wherein the holes are between about 0.4mm and 0.5mm in diameter.

41. The device of claim 38 fabricated from optically transparent and biocompatible material.

42. The device of claim 38 wherein the material is polycarbonate.

43. The device of claim 38 operable to be fixed by clamps under a microscope.

15 44. The system for automated cellular injection of claim 21 wherein the error detection means includes means detecting one or more errors from the group consisting of hardware problems, lighting problems, detecting failure of the tip of the micropipette, contact detection error, embryo recognition error, clogging of the micropipette tip, buckling of the micropipette, reaching motion limit of the first positioner or the second positioner, or on-line calibration error.

20

Application number / numéro de demande: 2560352

Figures: 10, 14

Pages: _____

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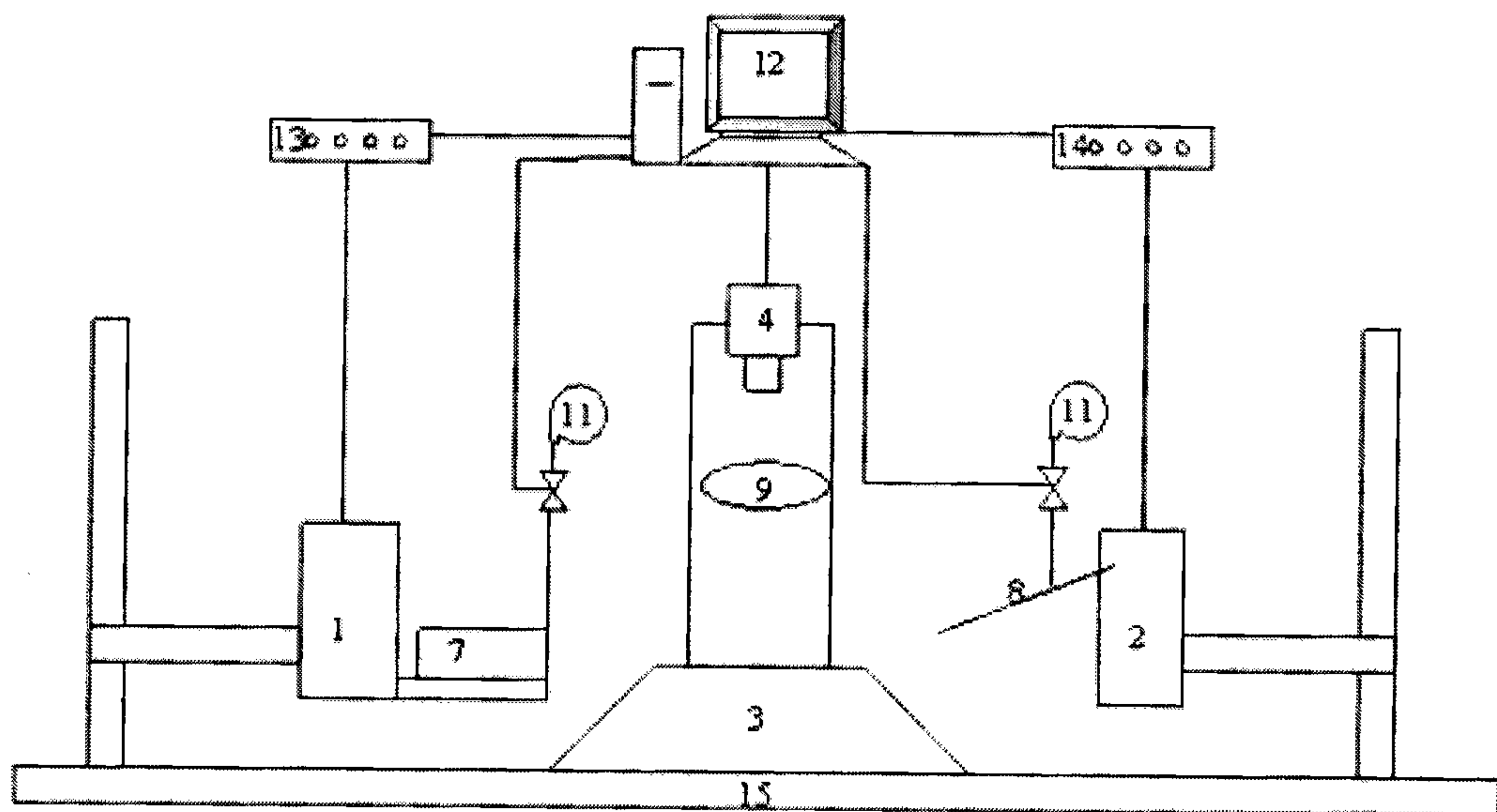


FIG. 1

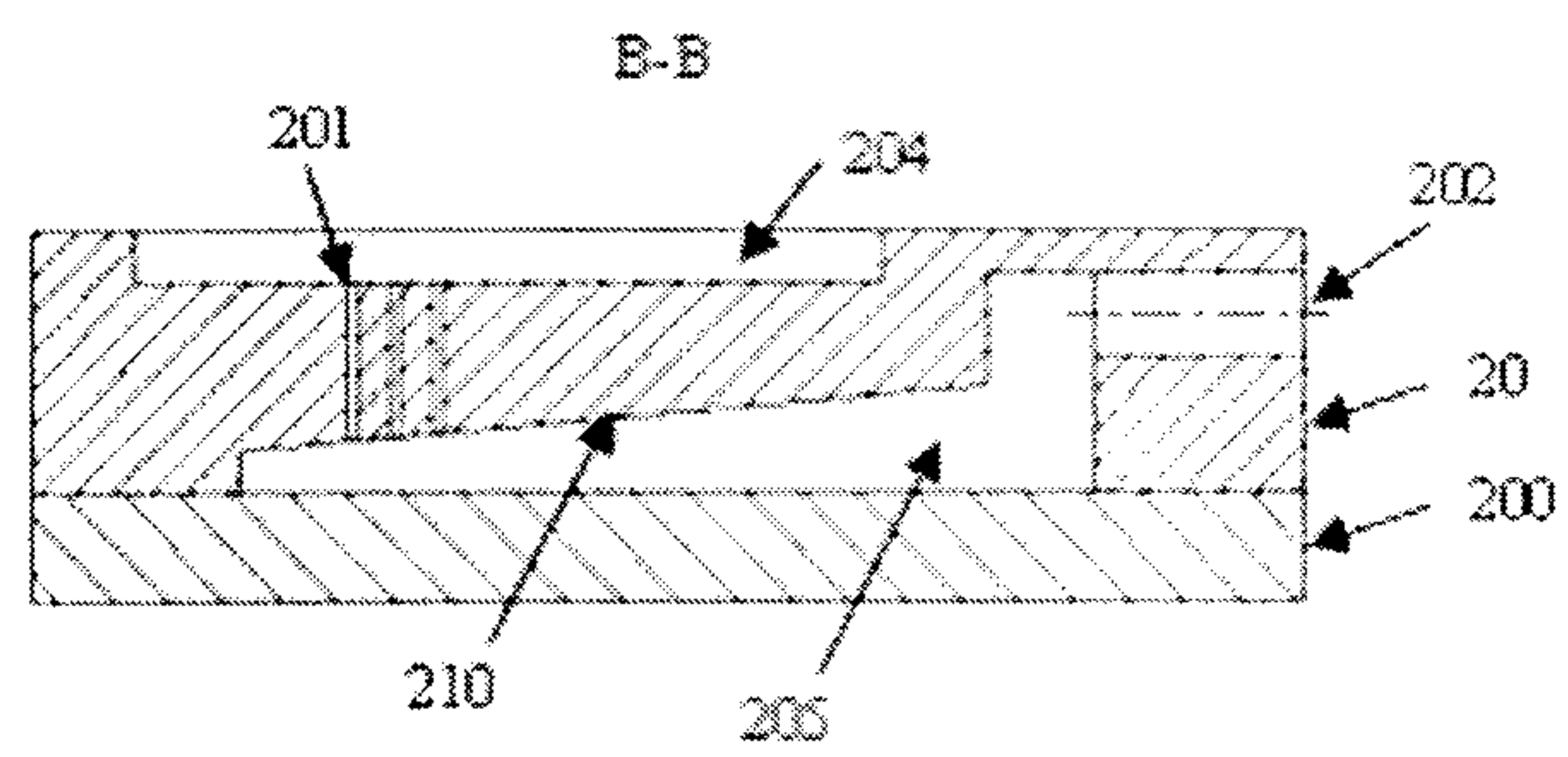
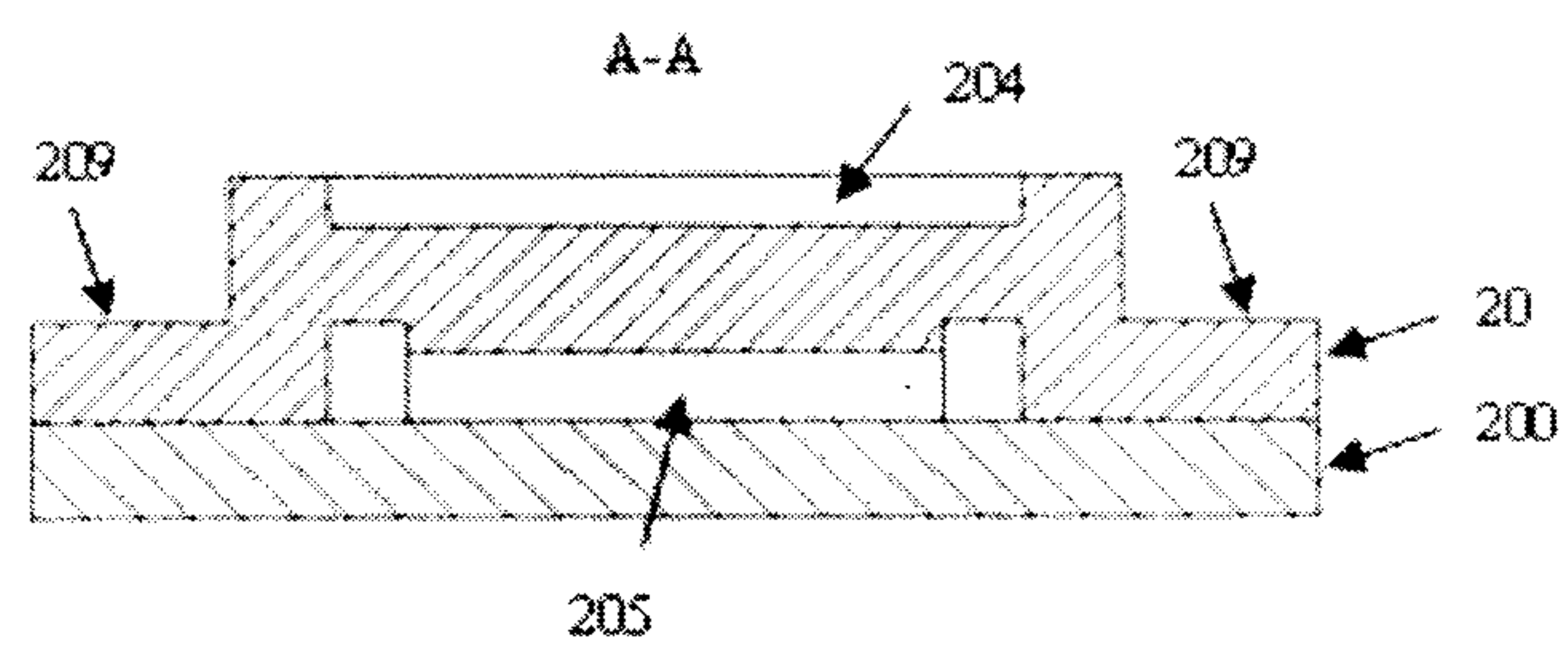
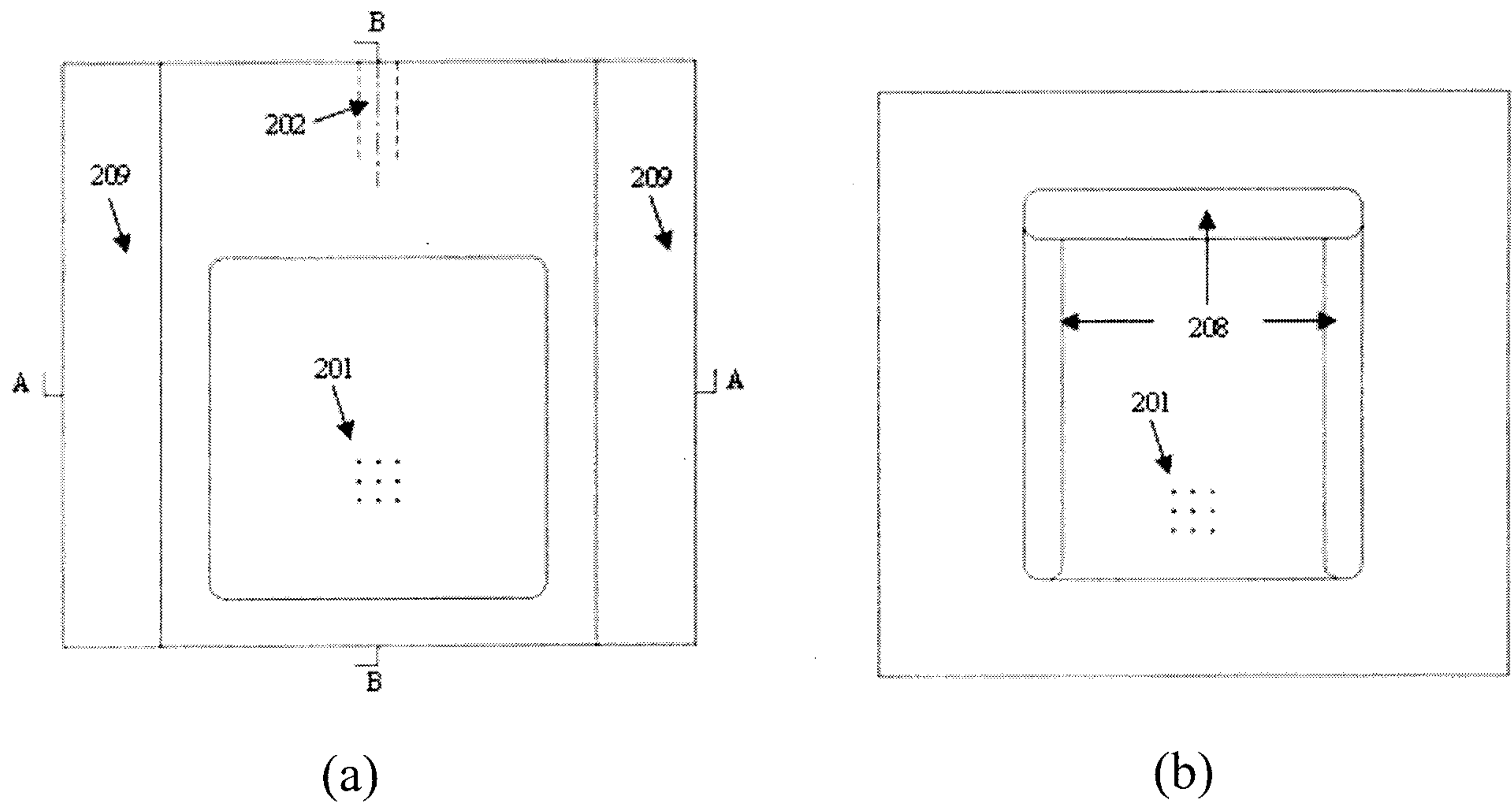


FIG. 2

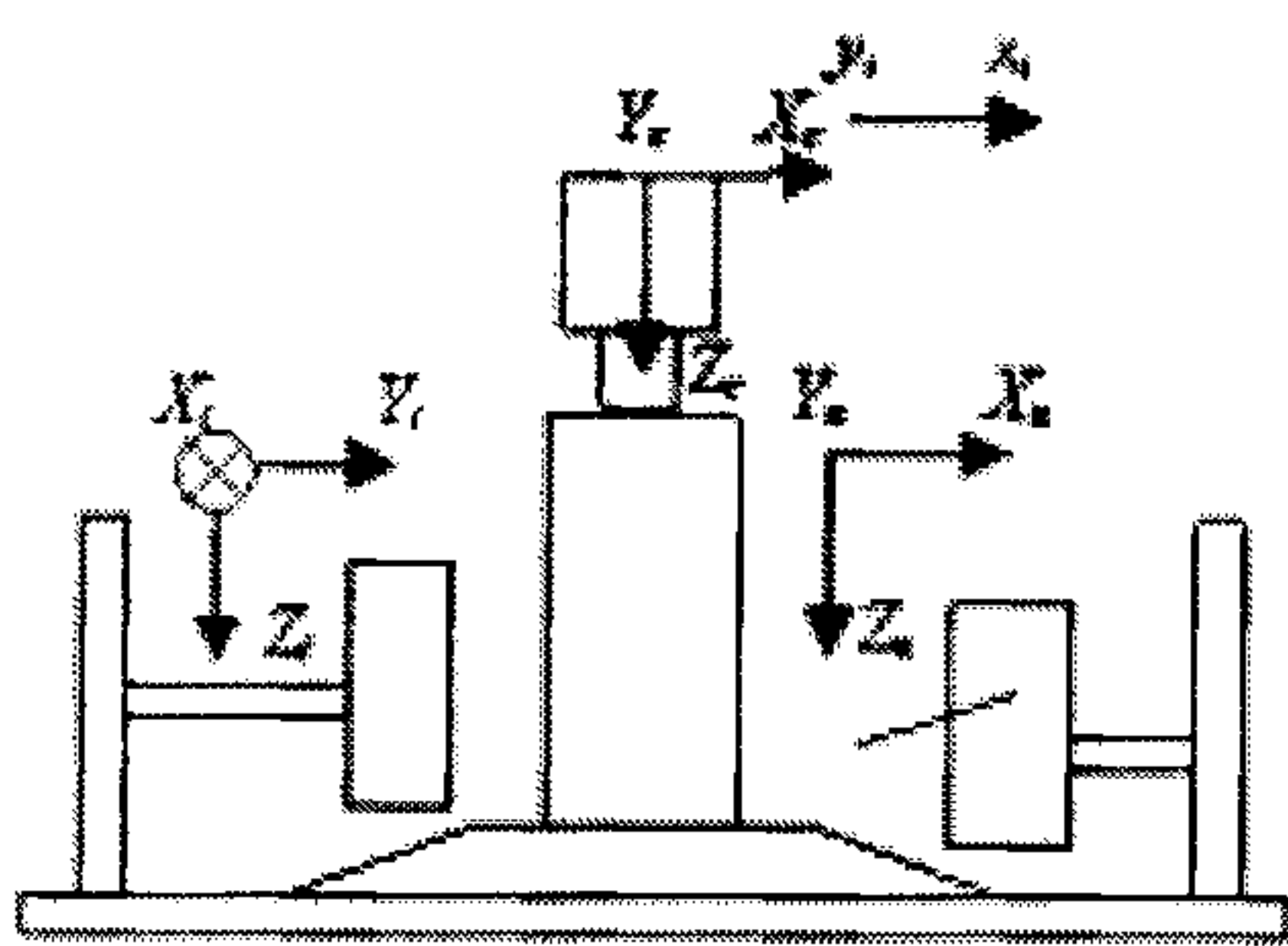


FIG. 3

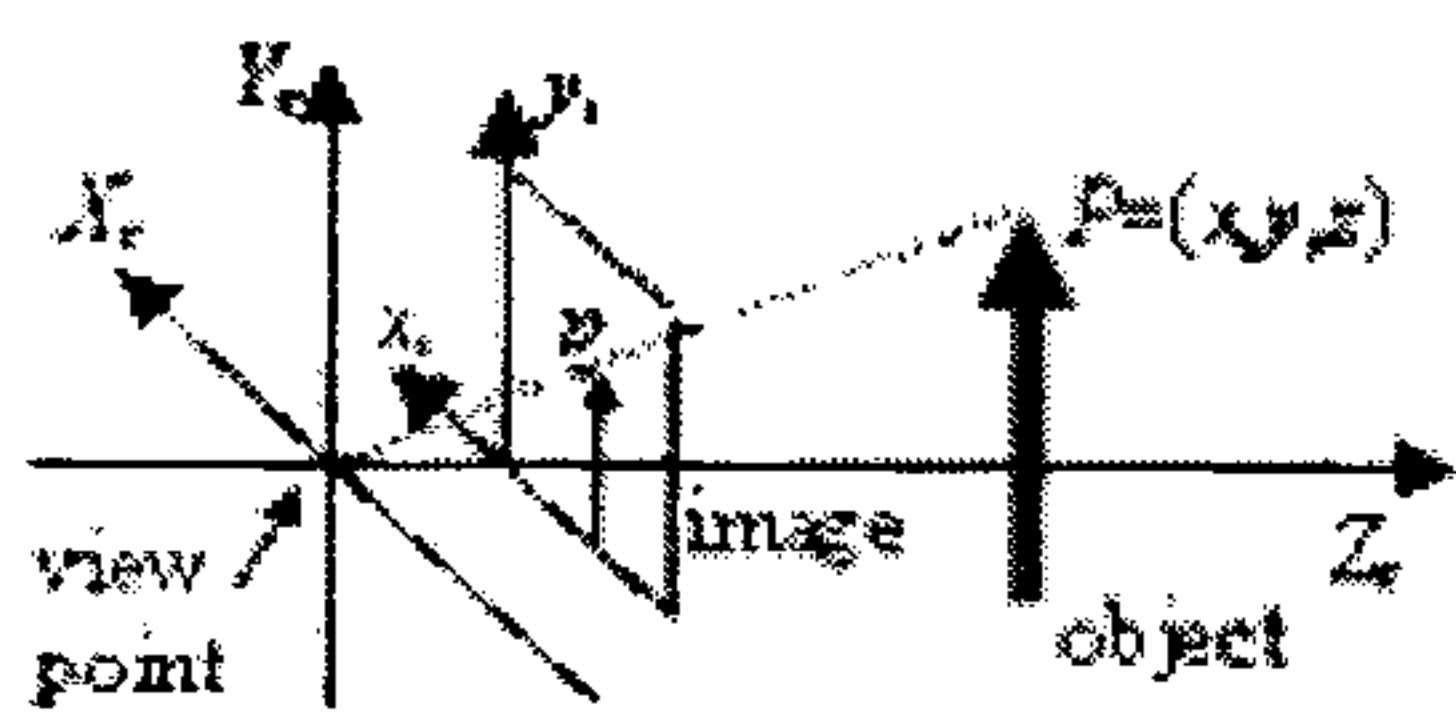


FIG. 4

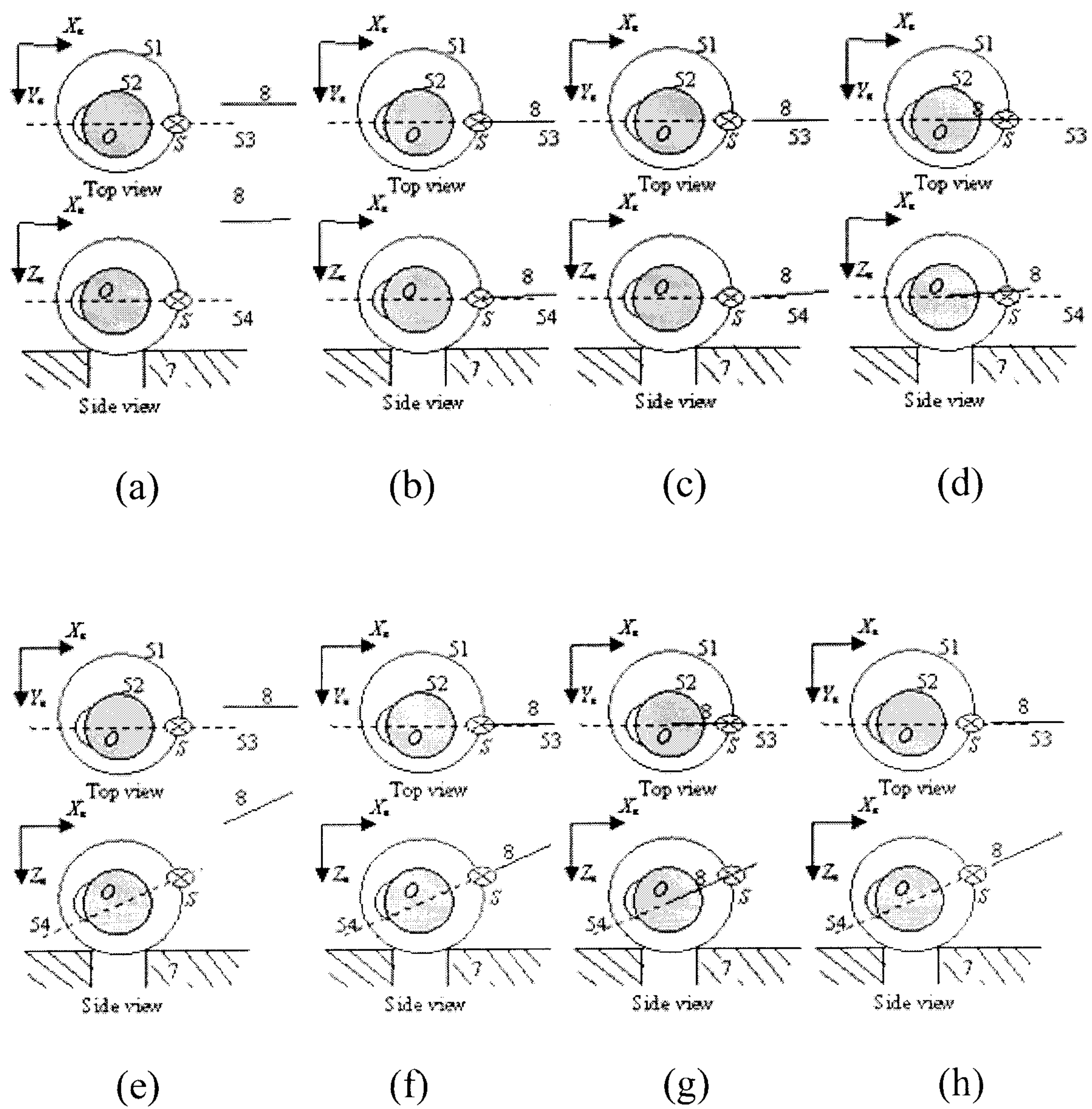


FIG. 5

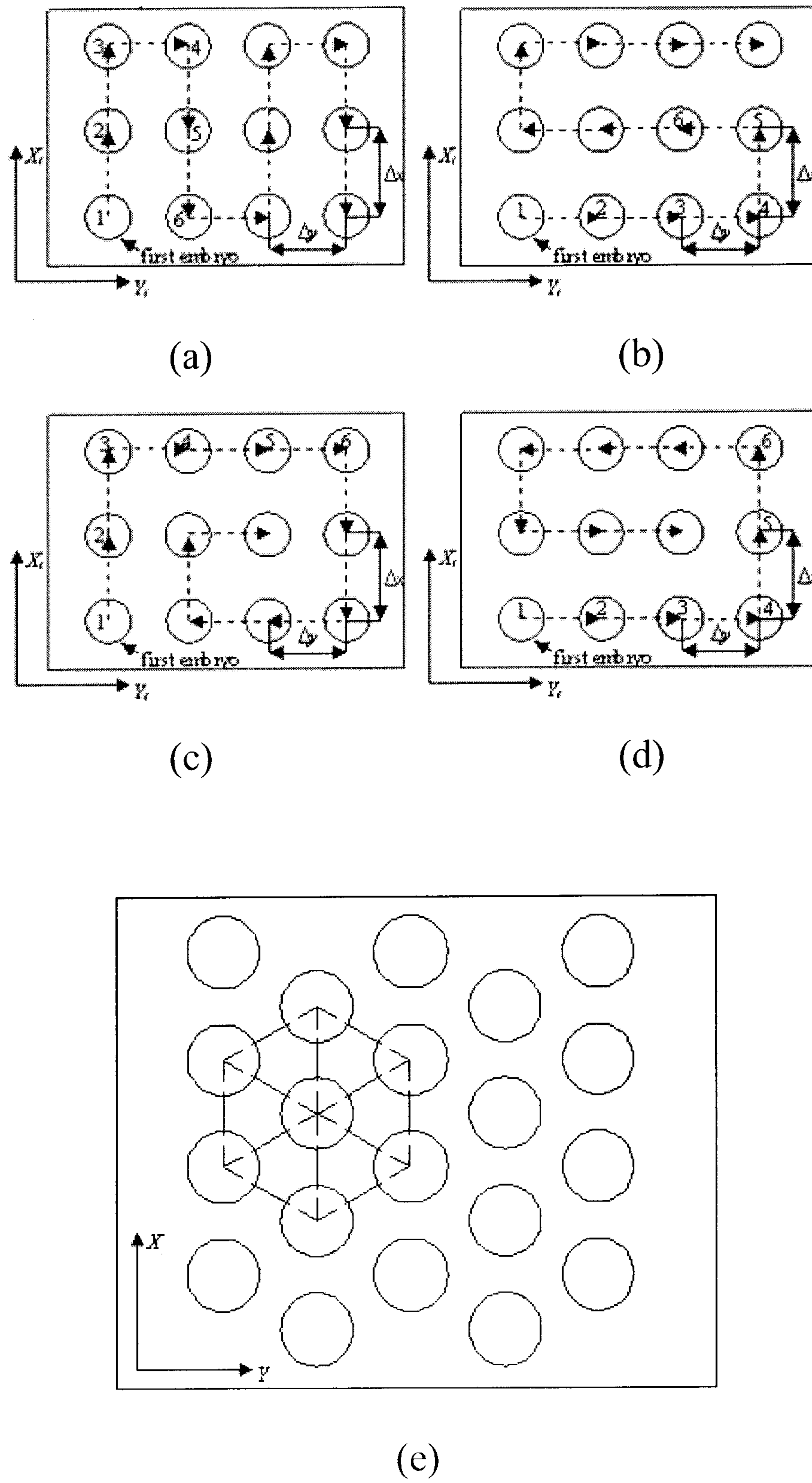


FIG. 6

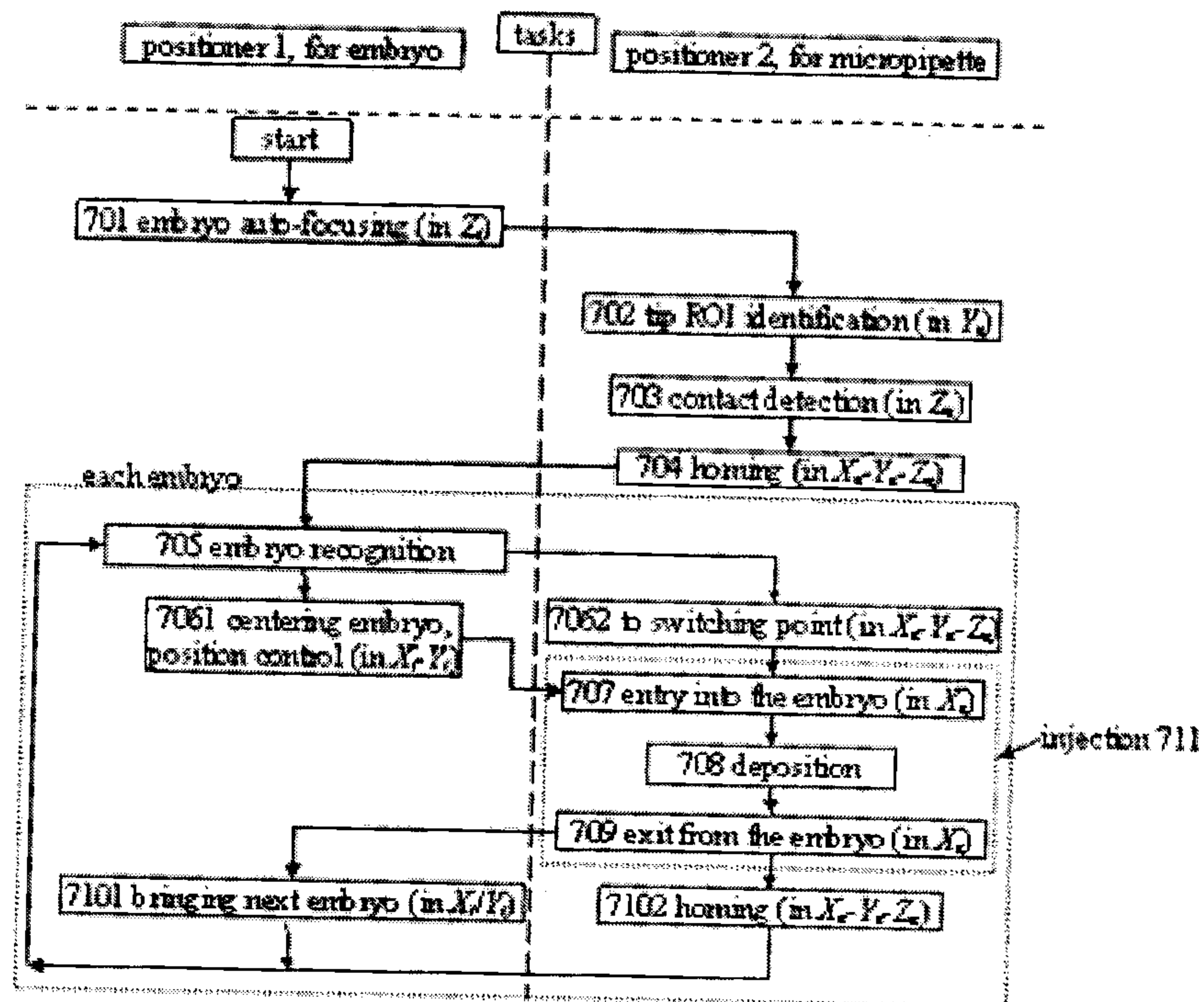


FIG. 7

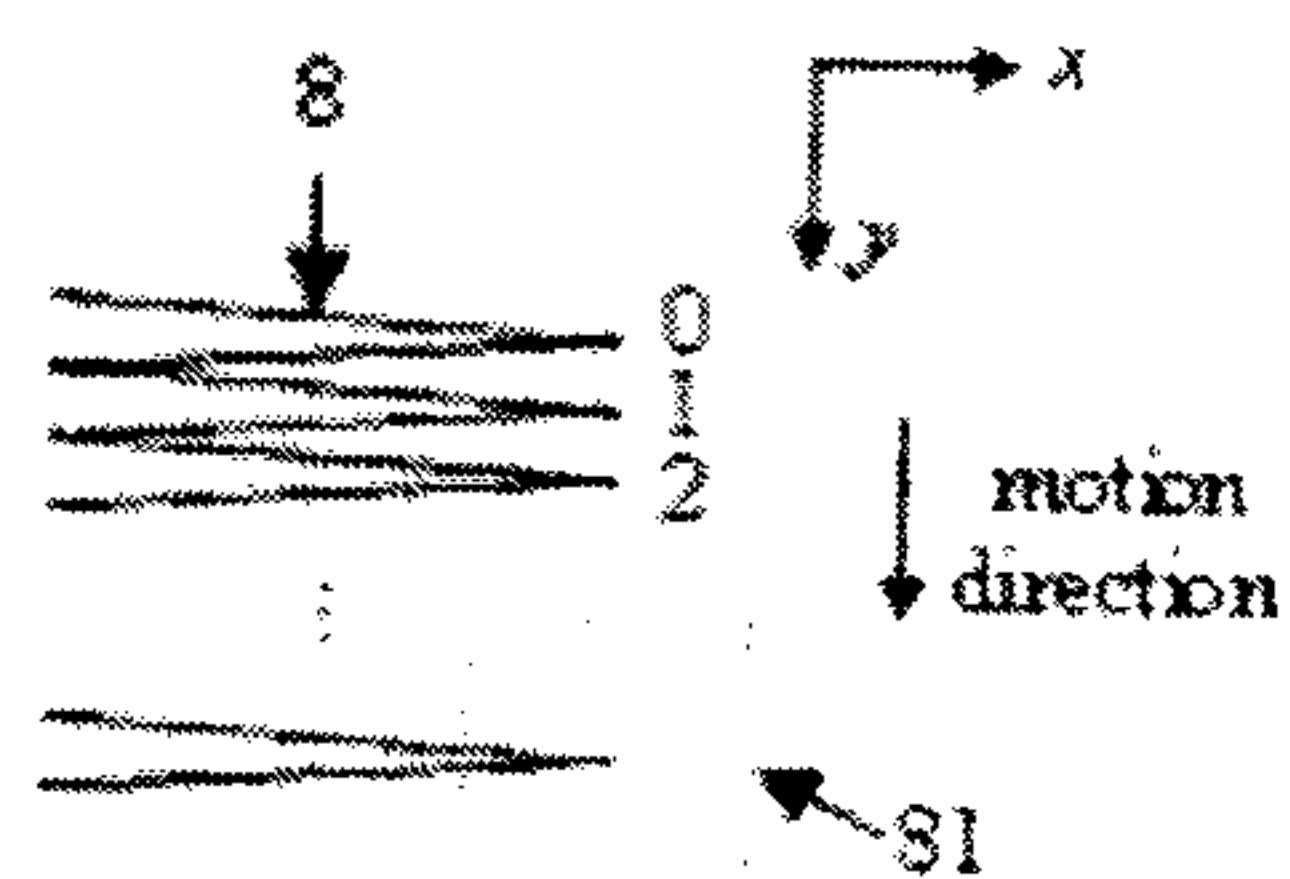


FIG. 8

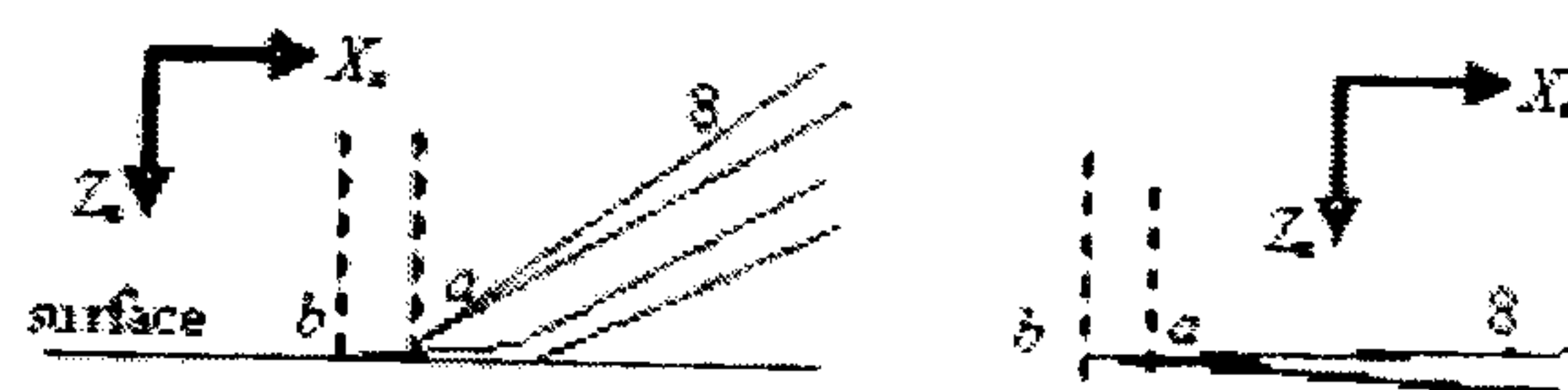


FIG. 9

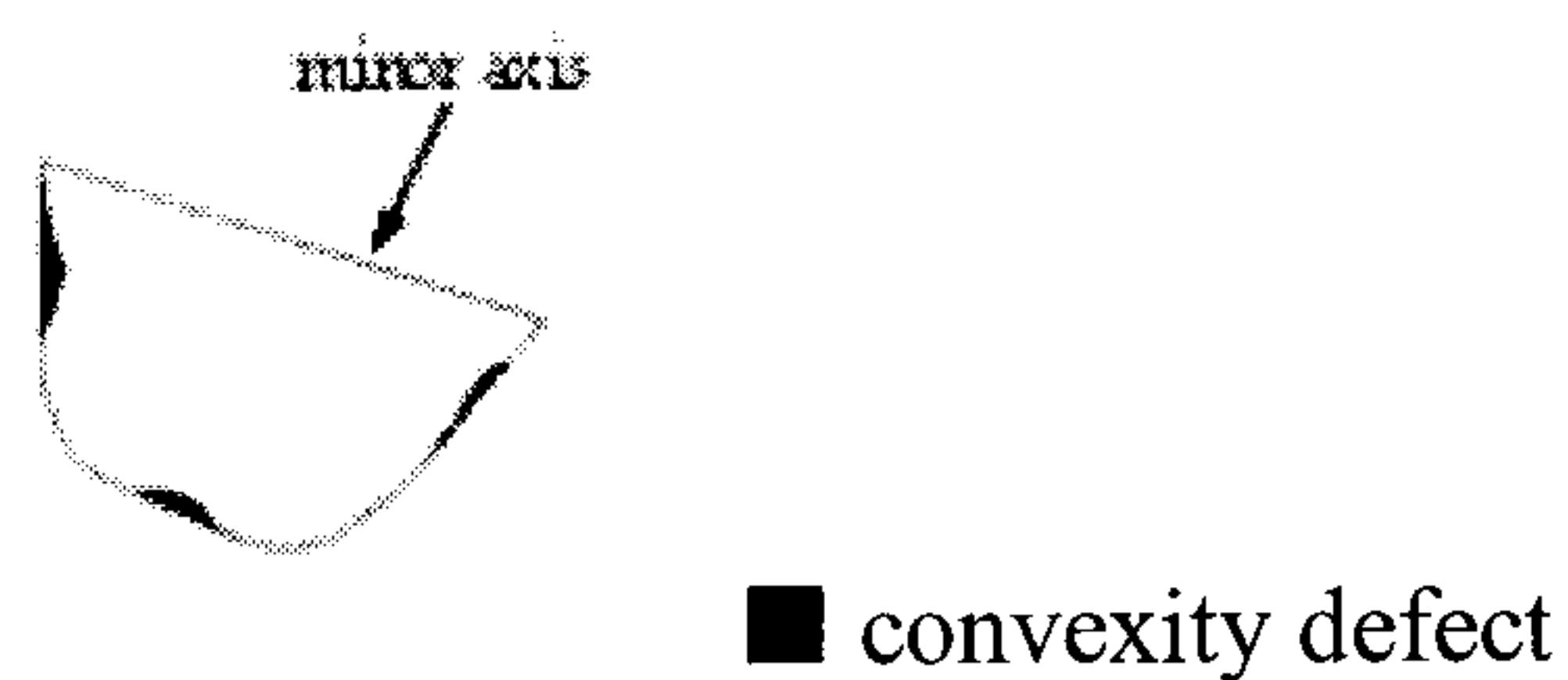


FIG. 11

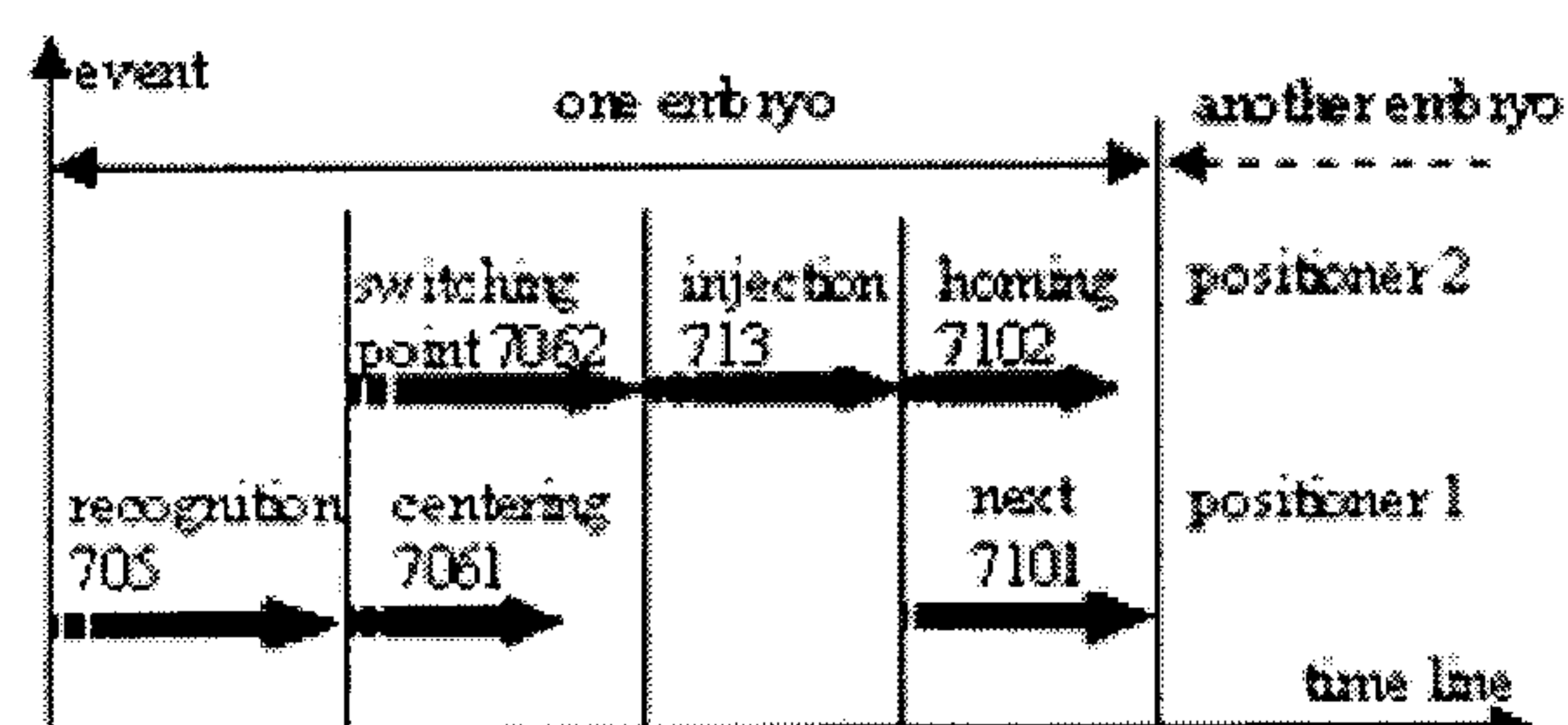


FIG. 12

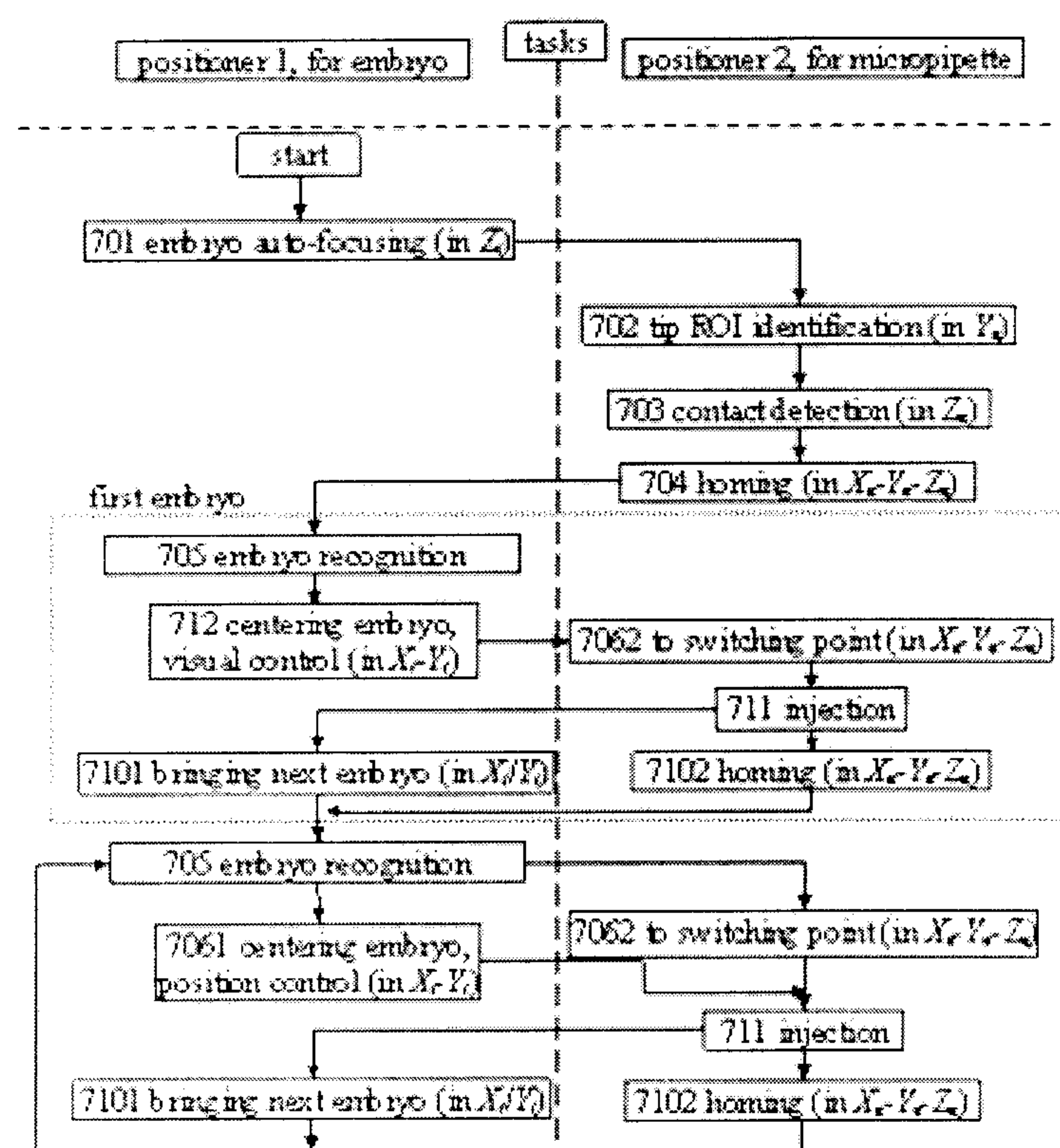


FIG. 13

