(54) Title: PUNCTURE CONTROL SYSTEM AND METHOD THEREFOR

FIG. 1
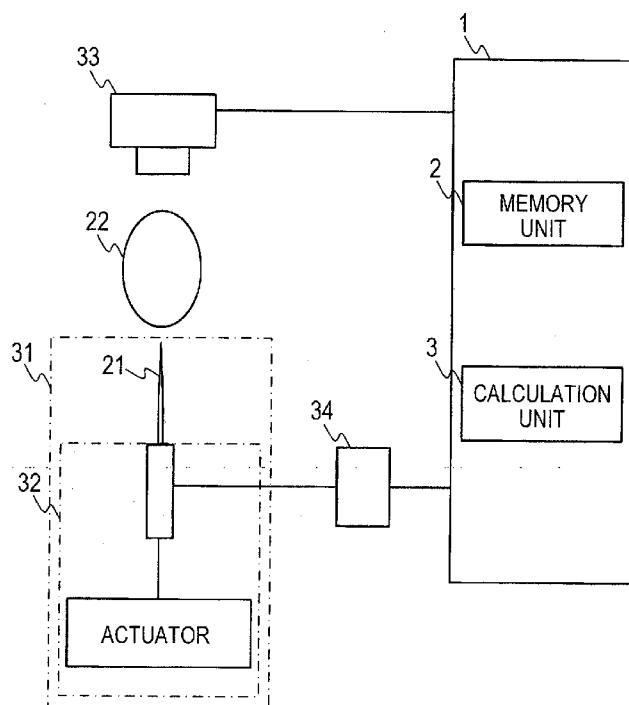
(57) **Abstract:** The puncture control system includes a trajectory error compensation filter for outputting a control signal for compensating for the error of a puncture needle from a target trajectory based on information on the position of the puncture needle obtained by a detector, a displacement compensation filter for which initial control parameters are determined based on a model representing characteristics of an organ, and an adder for outputting an added signal obtained by adding outputs of the trajectory error compensation filter and the displacement compensation filter. The organ model is used to predict a displacement of a puncture target position and sequentially determine a course of the puncture needle.

MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

DESCRIPTION
PUNCTURE CONTROL SYSTEM AND METHOD THEREFOR

Technical Field

[0001] The present invention relates to a puncture control
system using robot technologies and to a method for the
puncture control system.

Background Art

[0002] Minimum-invasive treatment are effective therapy
methods that place less physical burden on patients and
allow reductions in medical treatments after a surgery
and in rehabilitation period. As methods of minimum-
invasive percutaneous treatment, local therapies in
which a puncture needle is directly led to a tumor
tissue in an organ to necrotize the tumor tissue by a
radio wave, microwave, laser, or the like have been
attracting attention. There is also known a puncture
system in which a puncture needle is inserted to a skin
while a position of a tumor is confirmed by equipment
such as ultrasound, CT, or MRI so as to allow
confirmation that the needle has reached inside the
tumor.

[0003] In a puncture control system, it is required that a tip
of the puncture needle accurately reach a puncture
target position (for example, tumor tissue) in a tissue
of an organ. However, a puncture operation requires
skill and trial and error of a doctor because a
puncture error is generated, and is difficult even with
image guidance. The puncture error includes, for
example, a target trajectory error and a target
displacement error.

[0004] The target trajectory error is an error in which the
puncture needle itself deforms with a resistance while
traveling through the tissue of the organ, and because
the deformation is not uniform due to unevenness of the
tissue in a puncture route, a direction of travel of

the needle is displaced. The target displacement error
is an error that is generated because a target position
is moved when, while the needle travels through the
tissue of the organ, the tissue of the organ is
deformed by a force imparted to the organ by the needle
or the tissue is deformed with a change in direction of
gravitational force with respect to a posture of the
patient.

[0005] Such puncture error leads to a problem in that the tip
of the puncture needle does not accurately reach the
puncture target position in the tissue of the organ, or
in which the route through which the needle reaches the
puncture target position greatly differs from a planned
route because the puncture target position is moved.

[0006] In the conventional puncture control system, the
puncture error in which the puncture target position is
displaced when, while correcting a course of the needle,
the force of the tip of the needle is transferred to
the puncture target position through the tissue of the
organ has not been considered. Therefore, there are
known a system and a method in which the course
correction is performed every time the puncture target
position is displaced.

[0007] PTL 1 discloses a puncture control system for
correcting various kinds of information (general
information) of the general human liver to individual
information corresponding to the individual difference
of a puncture object patient. The puncture control
system combines information by a model obtained from
the individual information with force information and
visual information obtained by a force sensor and an
image acquisition device to decide a course of a needle,
and gives a drive command to an actuator.

Citation List

Patent Literature

[0008] PTL 1: Japanese Patent Application Laid-Open No. 2006-

271546
Summary of Invention
Technical Problem

[0009] FIG. 9A is a schematic diagram conceptually illustrating a process in which a puncture needle reaches a target position based on the disclosure of PTL 1.

[0010] First, a needle 21 is inserted to an organ O and toward a position T1 of the target position, which is confirmed in a state in which the needle 21 has not entered the organ. When the needle 21 is inserted to the organ O and travels therethrough (P1), the organ is deformed by the force imparted to an outer wall of the organ at the time of insertion and the force with which the needle 21 enters and travels through the organ to displace the target position from the position T1 to a position T2.

[0011] To adapt to the displacement, in the subsequent control step, a course of the needle is changed to P2 toward the moved target position T2. Then, due to the deformation of the organ caused by a pressing force of the needle 21 in its travel, the position T2 of the target position changes to a position T3, and due to this movement, the course of the needle 21 is changed to P3. Thereafter, in a similar manner, when the course of the needle 21 is changed to P3, the position T3 of the target position changes to a position T4, and when the course of the needle 21 is changed to P4, the position T4 of the target position changes to a position T5.

[0012] As described above, in the conventional course correction method, the actual displacement of the puncture target position is recognized in the image obtained in the next control step and the course of the needle is corrected again. In this method, the course correction of the needle allows the displacement of the

puncture target position, and the course of the needle
always follows the displacement. As a result, the
course vibrates or convergence takes time, which leads
to a problem in that a normal tissue is damaged or the
final puncture accuracy is not improved.

Solution to Problem

[0013] An object of the present invention is to provide a
puncture control system for use in an organ puncture
system, the organ puncture system including: a puncture
needle for which a control force and a control torque
are controlled by a manipulator and which moves toward
a target position of an organ; a detector for obtaining
information on a position of the puncture needle; and
an image obtaining unit for obtaining information on
the organ that changes with travel of the puncture
needle through the organ, the puncture control system
inputting a signal for controlling a position of a tip
of the puncture needle to the manipulator, the puncture
control system including: a trajectory error
compensation filter for outputting, based on the
information on the position of the puncture needle
obtained by the detector, a signal for compensating for
a displacement of the puncture needle from a target
trajectory; a displacement compensation filter for
which initial control parameters are determined so as
to correspond to a model representing characteristics
of the organ; and an adder for outputting a signal
obtained by adding the signal output by the trajectory
error compensation filter and the signal output by the
displacement compensation filter.

[0014] Further features of the present invention will become
apparent from the following description of exemplary
embodiments with reference to the attached drawings.

Brief Description of Drawings

[0015] FIG. 1 is a block diagram illustrating a configuration
of an organ puncture system according to the present

invention.

FIG. 2 is an explanatory diagram illustrating a relationship between a puncture needle and a target position of an organ according to the present invention.

FIG. 3 is a block diagram illustrating an extended system according to the present invention.

FIG. 4 is a block diagram illustrating a generalized plant according to the present invention.

FIG. 5 is a block diagram illustrating a control system according to the present invention.

FIGS. 6A and 6B are explanatory diagrams for illustrating relationships between trajectories of the puncture needle and positions of a puncture target position according to the present invention.

FIG. 7 is a block diagram illustrating the entire control system according to the present invention.

FIG. 8 is a flowchart illustrating a control sequence according to the present invention.

FIG. 9A is a conceptual diagram illustrating, based on the disclosure of PTL 1, a travel route of a puncture needle and how a target position of an organ moves, and FIG. 9B is a conceptual diagram illustrating, in a puncture control system to which the present invention is applied, a travel route of the puncture needle and how the target position of the organ moves.

Description of Embodiment

[0016] Preferred embodiments of the present invention will now be described in detail in accordance with the accompanying drawings.

[0017] Next referring to FIGS. 1 to 7, a puncture control system according to the present invention and an organ puncture system including the puncture control system are described.

[0018] FIG. 1 is a schematic diagram illustrating a configuration of the organ puncture system. The organ puncture system includes a puncture control system 1, a

needle robot 31, an image obtaining unit 33, and a
detector 34. The puncture control system 1 includes a
memory unit 2 and a calculation unit 3. The needle
robot 31 includes a puncture needle 21 and an
articulated manipulator 32 including an actuator. The
manipulator 32 holds the puncture needle 21 at its tip.
The puncture control system 1 performs, in a control
model stored in the memory unit 2, revision of control
input and control parameters of a model and the like by
the calculation unit 3 to output a signal for
controlling a position of the tip of the puncture
needle 21 to the manipulator 32.

[0019] The image obtaining unit 33 obtains information on the
organ that changes with the travel of the puncture
needle 21 in the organ. The detector 34 may obtain the
information on the puncture needle 21 that changes
momentarily as an image. The information on the organ
that is obtained as the image includes how the organ is
deformed and information on a position of a target
position of the puncture needle 21. The information on
the organ may also be obtained from an angle sensor.

[0020] FIG. 2 illustrates a concept of simultaneous control of
a trajectory of the puncture needle 21 and a change in
position of a puncture target position. The organ may
be expressed by a finite element model having arbitrary
numbers of elements and nodes. It is assumed that the
puncture needle 21 has entered an organ model 22 from
an ne-th node and its tip has reached an nt-th node.
The puncture needle 21 travels toward a position 24 of
the target position at an nb-th node. However, due to
a pressing force of the puncture needle 21, the actual
nb-th node of the target position moves from the
position 24 to a position 23 by a shift amount. The
shift amount is obtained as shifts u_{nb} and v_{nb} by the
image obtaining unit 33. The position of the tip of
the puncture needle 21 is detected and obtained by the

detector 34.

[0021] The present invention is intended to suppress the
change in position of the puncture target position.
Therefore, characteristics of the organ model 22 need
to be captured along with characteristics of the needle
robot 31. For that purpose, the organ model 22 is
included in the model of the needle robot 31 stored in
the memory unit of the puncture control system 1 as
follows to be modeled as an extended system 25.

[0022] 1) Modeling
Mass and a moment of inertia about the center of
gravity of the puncture needle 21 of the needle robot
31 are represented by m_n and J_n, respectively. It is
assumed that to shifts x_n and y_n of the center of
gravity and a rotation angle θ_n of the puncture needle
21, a control force f_x in an x direction and a control
force f_y in a y direction, which are imparted to the
puncture needle 21, and a control torque t_n about the
center of gravity are arbitrarily applied, respectively.
In this case, an equation of motion of the puncture
needle 21 is expressed by Equation (1).

$$M_n \ddot{q} = u, M_n = \begin{bmatrix} m_n & 0 & 0 \\ 0 & m_n & 0 \\ 0 & 0 & J_n \end{bmatrix}, q = \begin{bmatrix} x_n \\ y_n \\ \theta_n \end{bmatrix}, u = \begin{bmatrix} f_x \\ f_y \\ t_\theta \end{bmatrix} \tag{1}$$

[0023] When it is assumed here that

$$x = [q \; \dot{q}]^T$$

, an equation of state and an output equation of the
needle robot are expressed by Equations (2) and (3).

$$\dot{x} = A_n x + B_n u \tag{2}$$

$$y = C_n x \tag{3}$$

[0024] Next, it is assumed that the organ model 22 is a finite
element model having the number of elements m and the
number of nodes n. To the nodes divided by the finite

elements, a stiffness parameter, a mass parameter, and an attenuation parameter are distributed. Characteristics of the organ are represented by a stiffness matrix K, a mass matrix M, and an attenuation matrix C. The attenuation matrix C corresponds to attenuation amounts of the forces that have acted on the organ. When shifts in the x and y directions of an n-th node are represented by u_n and v_n and node forces that act are represented by f_{xn} and f_{yn}, a node displacement vector δ and a node force vector f as a whole may be expressed as follows.

$$\delta = \begin{bmatrix} u_1 & v_1 & \dots & u_n & v_n \end{bmatrix}^T, f = \begin{bmatrix} f_{x1} & f_{y1} & \dots & f_{xn} & f_{yn} \end{bmatrix}^T$$

[0025] When the vectors are used, the equation of motion is expressed by Equation (4) below.

$$M\ddot{\delta} + C(\delta, \dot{\delta})\dot{\delta} + K(\delta, \dot{\delta})\delta = f \qquad (4)$$

[0026] The second and third terms of Equation (4) indicate that the organ model 22 is a non-linear system in which stiffness and attenuation vary depending on shifts of the nodes.

[0027] When it is assumed that the force of the tip of the puncture needle 21 of the needle robot 31 is applied only on the nt-th node of the organ model 22, a node force f is expressed in matrix form by Equation (5).

$$f = \begin{bmatrix} 0_{2(nt-1)\times 1} & 0_{2(nt-1)\times 1} & 0_{2(nt-1)\times 1} \\ 1 & 0 & -l\sin\theta_n \\ 0 & 1 & l\cos\theta_n \\ 0 & 0 & 0 \\ \vdots & \vdots & \vdots \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} f_x \\ f_y \\ t_\theta \end{bmatrix} = F(q)u \qquad (5)$$

[0028] When it is assumed here that

$$x_o = \begin{bmatrix} \delta & \dot{\delta} \end{bmatrix}^T$$

, an equation of state of the organ model 22 can be written as Equation (6).

$$\dot{x}_o = \begin{bmatrix} 0 & I \\ -M^{-1}K(\delta,\dot{\delta}) & -M^{-1}C(\delta,\dot{\delta}) \end{bmatrix} x_o + \begin{bmatrix} 0 \\ M^{-1}F \end{bmatrix} u = A_o(x_o)x_o + B_o(q,x_o)u \qquad (6)$$

[0029] Further, when it is assumed that the nb-th node is the puncture target position and that the shifts u_{nb} and v_{nb} thereof may be observed by an image obtaining unit such as MRI, the output equation may be written as Equation (7).

$$y_o = \begin{bmatrix} 0_{1\times2(nb-1)} \, 1\, 0\, 0\, ... \, 0 \\ 0_{1\times2(nb-1)} \, 0\, 1\, 0\, ... \, 0 \end{bmatrix} x_o = C_o x_o \qquad (7)$$

[0030] Next, when a state of the extended system 25 of the needle robot and the organ model 22 is set as follows:

$$x_w = \begin{bmatrix} x & x_o \end{bmatrix}^T$$

, an equation of state and an output equation of the extended system 25 are expressed by Equations (8) and (9), respectively.

$$\dot{x}_w = \begin{bmatrix} A_n & 0 \\ 0 & A_o(x_o) \end{bmatrix} x_w + \begin{bmatrix} B_n \\ B_o(q,x_o) \end{bmatrix} u = A_w(x_w)x_w + B_w(x_w)u \qquad (8)$$

$$y_w = \begin{bmatrix} C_n & 0 \\ 0 & C_o \end{bmatrix} x_w = C_w x_w \qquad (9)$$

[0031] Based on Equation (8), the control input to the needle robot 31 becomes an input that allows, while changing the organ model 22, the needle robot 31 (actuator of manipulator 32) to be driven. In other words, through suitable determination of the control input, the shifts of the puncture needle 21 of the needle robot 31 and the shifts of the position 23 of the puncture target position in the organ model 22 may be adjusted simultaneously. A method of deriving the control input is described next.

[0032] FIG. 3 is a block diagram of the extended system 25. The model of the extended system 25 is the model expressed by Equation (8). The extended system 25

includes a block 26 of the needle robot 31 expressed by
Equation (2) and a block 27 of the organ model 22
expressed by Equation (6). Through a signal path 28,
the node to which the forces are applied in the organ
model 22 is changed by an output of the block 26.
Further, by a signal that passes through a signal path
29, the stiffness matrix K, the mass matrix M, and the
attenuation matrix C of the organ model 22 in the block
27 are revised.

[0033] 2) Control system of puncture control system

First, a target trajectory through which the tip of the
puncture needle 21 of the needle robot 31 reaches the
position 24 of the puncture target position is set.
Then, a control system is designed so that while the
needle robot 31 follows the target trajectory, the
displacement of the position 24 of the puncture target
position is minimized. In this embodiment, a feedback
control system is designed by using an H∞ control
system, but may be designed by using an optimal control
system or a model predictive control system.

First, a plant model that is generalized for designing
the H∞ control system is prepared. FIG. 4 illustrates
the plant model. In the figure, w_1, w_{21}, and w_{22} are
external inputs, z_1, z_{21}, and z_{22} are control amounts,
and filters 41, 42, and 43 are filters that use
weighting functions W_t, W_{s1}, and W_{s2}. In particular, z_{21}
and z_{22} are control amounts for a trajectory following
performance of the robot and the shifts of the puncture
target position, respectively. The weighting functions
are designed and the control amounts z_{21} and z_{22} from
the external input w_1 are evaluated, to thereby realize
minimization of a trajectory following error and the
displacement of the puncture target position
simultaneously. The control system to be designed
takes connection to the plant model (in practice, real
plant) into consideration, and is designed so as to

input y and y_o and output a control input u. When a transfer function of a closed-loop system including the plant model from an external input w_n to a control amount z_m and the control system is denoted by G_{zmwn}, the H∞ control system is designed using an evaluation function expressed by Equation (10) below.

$$\left\| \begin{matrix} G_{z_{22}w_1} \\ G_{z_{21}w_1} \end{matrix} \right\|_\infty < \gamma \qquad\qquad (10)$$

[0034] In the expression, G_{z21w1} represents a transfer function obtained by multiplying a setting function from the control input u to a position y of the tip of the puncture needle 21 of the needle robot 31 by the weighting function W_{s1}. A control system that minimizes an ∞ norm of the transfer function is determined to realize the trajectory following by the needle robot. Similarly, G_{z22w1} represents a transfer function obtained by multiplying a setting function from the control input u to a puncture target position y_o by the weighting function W_{s2}. A control system that minimizes an ∞ norm is determined so that the displacement of the puncture target position may be suppressed by the control input of the needle robot. G_{z21w1} and G_{z22w1} are evaluated simultaneously by Equation (10) to derive a control system that controls the trajectory following and the shifts of the puncture target position simultaneously. In Equation (10), the control system is determined so that γ is a positive number and takes as small a value as possible. Note that, when a model error and the like are taken into consideration, all evaluation paths G_{z1w1} may be used. The control system is realized by the following equation of state. In the equation, x_k is a state of the control system.

$$\dot{x}_k \;=\; A_k x_k + B_k y_w \tag{11}$$

$$u \;=\; C_k x_k + D_k y_w \tag{12}$$

[0035] FIG. 5 is a block diagram of a designed control system
10. The control system 10 corresponds to the equation
of state and the output equation expressed by Equations
(11) and (12). The control system 10 includes a
trajectory error compensation block 7, a displacement
compensation block 8, and an adder 13. First, a
difference signal input (r-y) representing a difference
between a position r of the target trajectory and the
actual position y of the puncture needle 21 is input to
the trajectory error compensation block 7 so that a
signal of the position y of the puncture needle 21
approaches the position r of the target trajectory.
Then, the trajectory error compensation block 7
generates and outputs a trajectory compensation signal
u' so that the difference signal input (r-y) is reduced,
the trajectory compensation signal u' being a control
input that compensates for the trajectory following
error of the needle robot 31 corresponding to the
position of the puncture needle 21. Moreover, control
parameters of the trajectory error compensation block 7
are revised so that the state x_w of the real plant that
changes with the position y of the puncture needle 21
represents actual characteristics of the organ in a
state in which the puncture needle 21 is traveling
through the organ. The trajectory error compensation
block 7 having the revised control parameters may
generate and output the trajectory compensation signal
u' so as to suit the state - x_w of the real plant in
the actual state in response to the difference signal
input (r-y). The trajectory compensation signal u' is
the control input that compensates for the trajectory
following error of the needle robot 31 corresponding to
the position of the puncture needle 21.

[0036] The displacement compensation block 8 determines initial control parameters based on the organ model 22 representing the characteristics of the organ. When the signal of the position y_0 of the puncture needle 21 is input to the displacement compensation block 8, the displacement compensation block 8 generates and outputs a portion compensation signal u'' so that the puncture needle minimizes the displacement of the puncture target position in the organ. In the displacement compensation block 8, control parameters of the displacement compensation block 8 are revised so that the state x_w of the real plant represents the actual characteristics of the organ in the state in which the puncture needle 21 is traveling through the organ. The displacement compensation block 8 having the revised control parameters generates and outputs the portion compensation signal u'' corresponding to the displaced position of the puncture target position in the organ so as to suit the state x_w of the real plant in the actual state in response to the signal of the position y_0.

[0037] The adder 13 adds the output u' of the trajectory error compensation block 7 and the output u'' of the displacement compensation block 8 to output the control input u. Based on the control input u, the actuator of the needle robot 31 is driven so as to control the position of the puncture needle 21. Then, the puncture needle travels with the control forces and the control torque corresponding to the control input u to change the position of the target position. The position of the target position is obtained as the state x_w of the real plant by the image obtaining unit 33. Based on the state x_w of the real plant, the control parameters (of the organ model 22) of the displacement compensation block 8 are revised so as to represent the actual characteristics of the organ in the state in

which the puncture needle 21 is traveling through the
organ.

[0038] The trajectory error compensation block 7 and the
displacement compensation block 8 are provided in the
calculation unit 3 of the puncture control system 1 as
a trajectory error compensation filter 7 and a
displacement compensation filter 8, respectively.

[0039] The trajectory compensation signal u', the portion
compensation signal u'', and the added signal u are
expressed as vector quantities having $u'=[f_x', f_y', t_\theta']^T$,
$u''=[f_x'', f_y'', t_\theta'']^T$, $u=[f_x, f_y, t_\theta]^T$ as their
components, respectively. In practice, the components
of the control input vectors u' and u'' are output
depending on the state of the needle robot 31 and the
state of the organ model 22. For simplification, only
a control torque t_θ is described here, but the same is
applied to the control forces f_x and f_y which are the
other components applied to the puncture needle 21.

[0040] As illustrated in FIG. 6A, a case where a puncture
error due to the resistance of the organ causes the tip
of the puncture needle 21 of the needle robot 31 to be
deviated from the trajectory in a negative direction of
a y coordinate and the position 24 of the puncture
target position is moved to the position 23 in the
negative direction of the y coordinate is taken as an
example. In this case, the trajectory error
compensation filter 7 outputs a positive value as a
control torque t_θ' so as to make the needle robot
follow the trajectory. Moreover, the displacement
compensation filter 8 functions so as to reduce the
shift of the puncture target position to 0 by the
control input to the needle robot 31, and hence outputs
a positive value as a control torque t_θ''. The two
signals are added by the adder 13, and hence the input
signal is generated so that the displacement of the
puncture target position is minimized by the

displacement compensation filter 8 having the revised
control parameters. In this manner, trajectory control
of the needle robot as well as control to minimize the
displacement of the puncture target position is
realized.

[0041] Next, as illustrated in FIG. 6B, a case where the tip
of the puncture needle 21 of the needle robot 31 is
deviated from the trajectory in the negative direction
of the y coordinate and the shift of the puncture
target position is moved in a positive direction of the
y coordinate is taken as an example. In this case, the
trajectory error compensation filter 7 outputs a
positive value as the control torque t_θ' so as to make
the needle robot follow the trajectory. The
displacement compensation filter 8 functions so as to
reduce the shift of the puncture target position to 0
by the control input to the needle robot, and hence
outputs a negative value as the control torque t_θ''.

[0042] The control parameters of the displacement compensation
filter 8 are changed by the organ model 22 to generate
the input $u'' = [f_x''\ f_y''\ t_\theta'']^T$ that moves the shift of
the puncture target position to a direction opposite to
the direction of movement of the target position.

[0043] Those two signals t_θ' and t_θ'' are added by the adder
13, with the result that the control torque t_θ for
driving the needle robot 31 becomes a value smaller
than t_θ' that takes driving of the needle robot alone
into consideration. In other words, the input $u'' = [f_x''$
$f_y''\ t_\theta'']^T$ for moving the shift of the puncture target
position in such a direction as to maintain the initial
position as much as possible is generated.

[0044] As a result, an operation in which the needle robot
gradually recovers to the trajectory while minimizing
the displacement of the puncture target position is
realized. In other words, at a position where the
effects of the control torque t_θ on the puncture target

position are reduced, the puncture needle quickly
recovers to the trajectory. When the recovery to the
trajectory is too gradual, the weighting functions W_{s1}
and W_{s2} may be adjusted based on numerical simulation.

[0045] In FIGS. 6A and 6B, the cases where the tip of the
puncture needle 21 of the needle robot 31 is deviated
from the trajectory in the negative direction of the y
coordinate have been described, but the same applies to
a case where the tip of the puncture needle 21 of the
needle robot 31 is deviated from the trajectory in the
positive direction of the y coordinate. In this case,
the sign of the value of t_θ'' described above may be
inverted.

[0046] FIG. 7 is a block diagram of a case where a real plant
40 of the puncture system is applied to the control
system of the extended system 25. In this case, the
real plant 40 corresponds to the extended system 25
expressed by Equation (8), and is a time-variant system
in which a system matrix and a control input matrix
vary depending on the state.

[0047] The control input u output from the control system 10
illustrated in FIG. 5 is input to the real plant 40.
The control input u is input to the manipulator 32,
which is the real plant, and output as the control
forces and the control torque for the puncture needle
21. The puncture needle 21 controlled by the control
forces and the control torque deforms the organ, which
leads to a change in characteristics of the organ, such
as a displacement of the target position. The
characteristics are obtained as the state by the image
obtaining unit 33. The obtained state is input to the
trajectory error compensation filter 7 and the
displacement compensation filter 8. The control
parameters of each of the trajectory error compensation
filter 7 and the displacement compensation filter 8 are
revised by the input state. Based on the state of the

organ that changes with the travel of the puncture
needle 21, the control parameters of each of the
trajectory error compensation filter 7 and the
displacement compensation filter 8 are sequentially
revised in time series. In other words, the control
parameters are revised based on the changing state of
the organ, and hence the added signal u becomes an
input signal that minimizes the displacement of the
target position to be punctured and causes the puncture
needle 21 to gradually recover to the trajectory.

[0048] Further, the filters of the weighting functions in the
paths of the control amounts z_{21} and z_{22} illustrated in
the plant model of FIG. 4 may be added to an output
line of the real plant 40 of FIG. 7. Those filters
multiply the output of the state defined by the
information on the position of the puncture needle 21,
which is obtained by the detector 34, and the
information on the organ, which is obtained as an image
by the image obtaining unit 33, by the weighting
functions. In this manner, in revising the control
parameters of each of the trajectory error compensation
filter 7 and the displacement compensation filter 8,
the effects of the control forces and the control
torque imparted to the puncture needle 21 may be
changed.

[0049] 3) Control sequence of puncture control system

The H∞ control theory does not compensate for the
control performance of the time-variant system.
Therefore, the puncture control is performed using a
control sequence illustrated in FIG. 8. Steps of the
control sequence are described below.

1. A trajectory that connects the puncture target
position and a puncture portion is generated (S01).

2. The tip of the puncture needle 21 of the needle
robot is moved to the ne-th node (u_{ne}, v_{ne})
corresponding to the puncture portion of the organ

model 22 (S01).

3. The nt-th node to which the forces of the needle
robot are applied is set to the ne-th node (S01). The
state x_w of the extended system is initialized (S01).
The displacement compensation filter 8 determines
initial control parameters so as to correspond to the
organ model 22.

4. The extended system model of Equation (8) is derived.
In order to derive the control system, the extended
system model is revised (S02). In the revision, order
reduction is performed by a modal truncation method or
the like.

5. The control system based on the evaluation function
of Equation (10) is derived (S03).

6. A shift y of the puncture needle 21 of the needle
robot and a shift y_o of the puncture target position of
the organ are obtained using the angle sensor, an image,
and the like (S04).

7. When the tip of the puncture needle 21 of the needle
robot has reached the target position of the organ, the
control sequence is ended, and when the tip of the
puncture needle 21 of the needle robot has not reached
the target position, the steps are continuously
performed (S05).

8. The control input u is generated using displacement
information y and y_o and Equation (12) (S06).

9. The control input u is applied to the extended
system (S07), and the state x_w is calculated (S08).

10. The control input u is applied to drive the needle
robot 31 for a period of sampling time Δt (S09). The
displacement information of the target position, which
is displaced with the travel of the puncture needle 21
through the organ, is obtained by an image obtaining
device (S10). Moreover, the information on the
position of the tip portion of the puncture needle 21
is obtained by the detector (S10).

11. A stress and the like of the tip portion of the
puncture needle of the needle robot are calculated or
at the same time pieces of the displacement information
of the model are compared by using the extended system
model to identify which node of the organ model 22 the
displacement of the tip of the needle robot corresponds
to (S11).

12. The sequence returns to the step of revising the
extended system model (S02).

[0050] In summary, the organ puncture system according to the
present invention operates as follows.

[0051] As illustrated in FIG. 9B, first, the puncture needle
21 is inserted to the organ O and toward the position
T1 of the target position obtained in the state before
the puncture needle 21 enters into the organ. When the
puncture needle 21 is inserted to and travels through
the organ (P1), it is expected that the organ is
deformed by the force imparted to the outer wall of the
organ at the time of insertion and the force with which
the puncture needle 21 travels through the organ, so
that the position T1 of the target position is
displaced to the position T2. The shifts are predicted,
the organ model 22 is revised based on the state
variables in the subsequent real control step, and the
output of the organ model 22 is used to change a course
toward the target position T2 in the expected direction
of movement to P2. In this manner, the target position
is displaced to return to the T1 side.

[0052] Further, on the other hand, when the shifts are beyond
the initial target position T1, for example, the course
toward the target position T3 in the expected direction
of movement is changed to P3 so that the target
position is displaced to return to the T1 side.

[0053] In other words, the organ puncture system sequentially
determines a direction of travel of the puncture needle
21 so as to cause a minimum displacement that allows

the target position to maintain the initial position.

Advantageous Effects of Invention

[0054] According to the present invention, the puncture needle may accurately reach the target position while minimizing the displacement of the puncture target position. Therefore, a medical robot system for performing punctuation with high accuracy without damaging normal tissues is provided.

[0055] While the present invention has been described with reference to exemplary embodiments, it is to be understood that the invention is not limited to the disclosed exemplary embodiments. The scope of the following claims is to be accorded the broadest interpretation so as to encompass all such modifications and equivalent structures and functions.

[0056] This application claims the benefit of Japanese Patent Application No. 2012-142961, filed June 26, 2012, which is hereby incorporated by reference herein in its entirety.

CLAIMS

[1]   A puncture control system comprising:
a puncture needle for which a control force and a
control torque are controlled by a manipulator to move
toward a target position of an organ;
a detector for obtaining information on a position of
the puncture needle; and
an image obtaining unit for obtaining information on
the organ that changes with travel of the puncture
needle through the organ, the puncture control system
inputting a signal for controlling a position of a tip
of the puncture needle to the manipulator,
wherein the puncture control system comprising:
a trajectory error compensation filter for outputting a
signal for compensating for a displacement of the
puncture needle from a target trajectory, based on the
information on the position of the puncture needle
obtained by the detector;
a displacement compensation filter for which initial
control parameters are determined so as to correspond
to a model representing characteristics of the organ;
and
an adder for outputting a signal obtained by adding the
signal output by the trajectory error compensation
filter and the signal output by the displacement
compensation filter,
wherein the puncture needle with the control force and
the control torque controlled by the signal output by
the adder travels through the organ to change a state
of the organ,
wherein control parameters of each of the trajectory
error compensation filter and the displacement
compensation filter are revised based on the state of
the organ obtained by the image obtaining unit, and
wherein the signal obtained by adding, by the adder,
the signals output from the trajectory error

compensation filter and the displacement compensation
filter whose the control parameters are revised is a
signal that minimizes the displacement of the target
position.

[2]   A puncture control system according to claim 1, further
comprising a filter for multiplying the information of
the position of the puncture needle, which is obtained
by the detector, and the state of the organ, which is
obtained by the image obtaining unit, by weighting
functions.

[3]   A puncture control system according to claim 1 or 2,
wherein the characteristics of the organ comprise
stiffness, mass, and an attenuation amount of a force
that has acted on the organ.

[4]   An organ puncture system, comprising:
a manipulator;
a puncture needle for which a control force and a
control torque are controlled by the manipulator to
move toward a target position of an organ;
a detector for obtaining information of a position of
the puncture needle;
an image obtaining unit for obtaining a position of the
target position that is displaced with travel of the
puncture needle through the organ as an image; and
a puncture control system according to claim 1 or 2.

[5]   A puncture control method for controlling a position of
a puncture needle that moves toward a target position
of an organ, the puncture needle changing a state of
the organ with travel through the organ,
wherein the puncture control method comprises
sequentially determining a direction of travel of the
puncture needle according to the travel of the puncture
needle so as to minimize a displacement of the target
position.

[6]   A puncture control method according to claim 5, further
comprising controlling, with an added signal obtained

by adding a trajectory compensation signal for
compensating for a displacement of the puncture needle
from a target trajectory based on the information on
the position of the puncture needle and a portion
compensation signal corresponding to a position of a
displaced puncture target position in the organ, a
control force and a control torque to be imparted to
the puncture needle,
wherein control parameters for generating each of the
trajectory compensation signal and the portion
compensation signal are revised based on a state of the
organ, and
wherein the added signal having the control parameters
revised is a signal that minimizes the displacement of
the target position.

FIG. 1
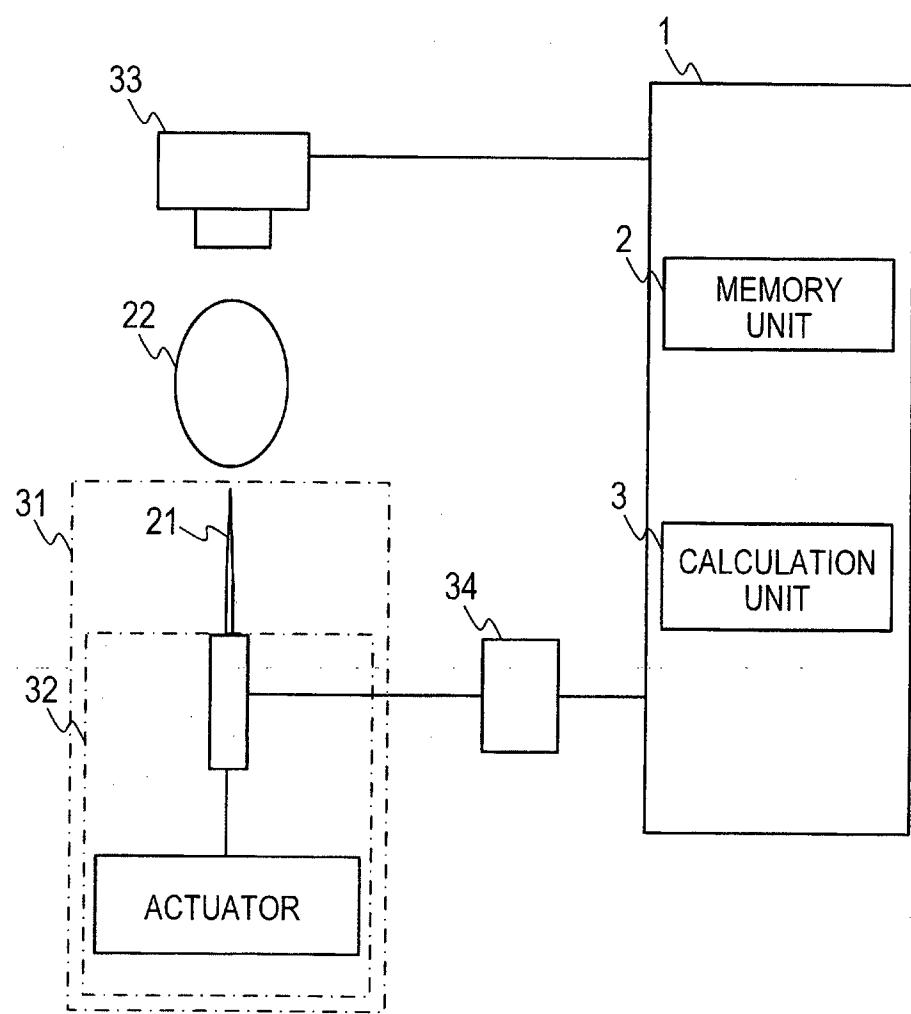
## FIG. 2
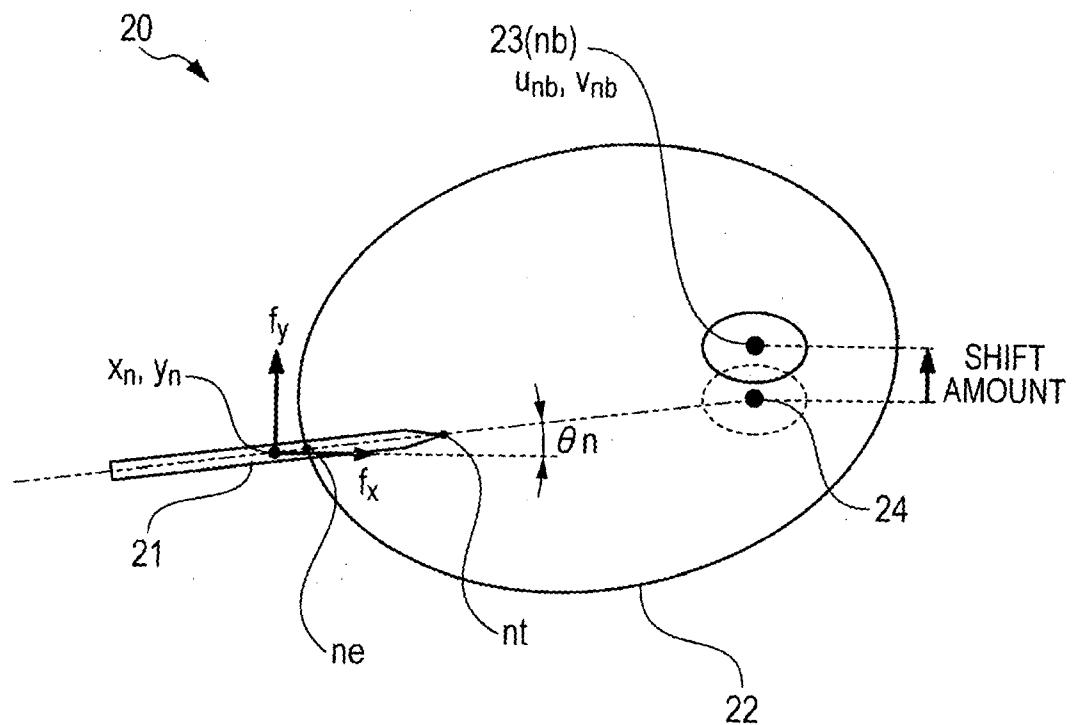
FIG. 3
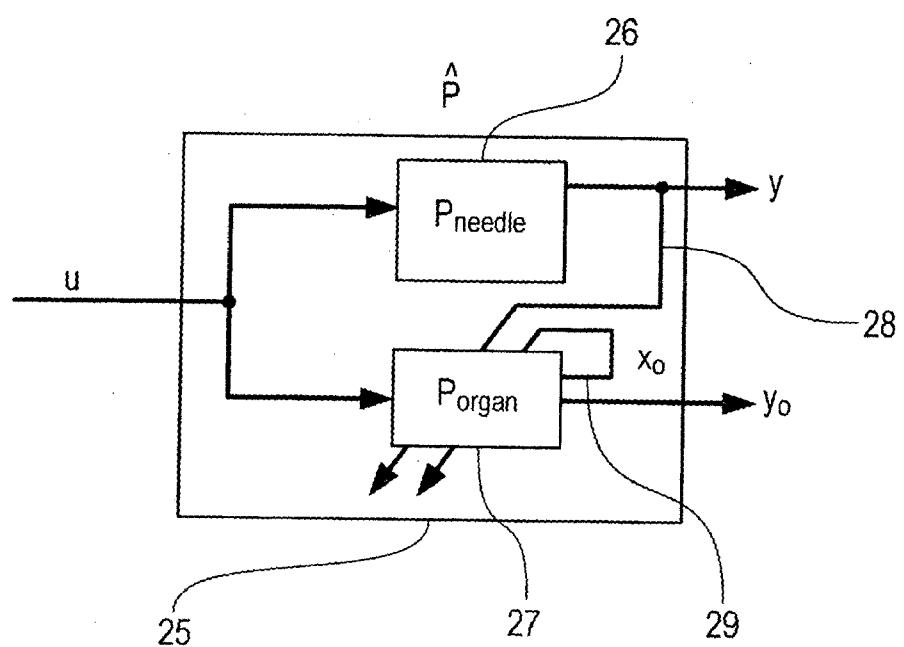
FIG. 4
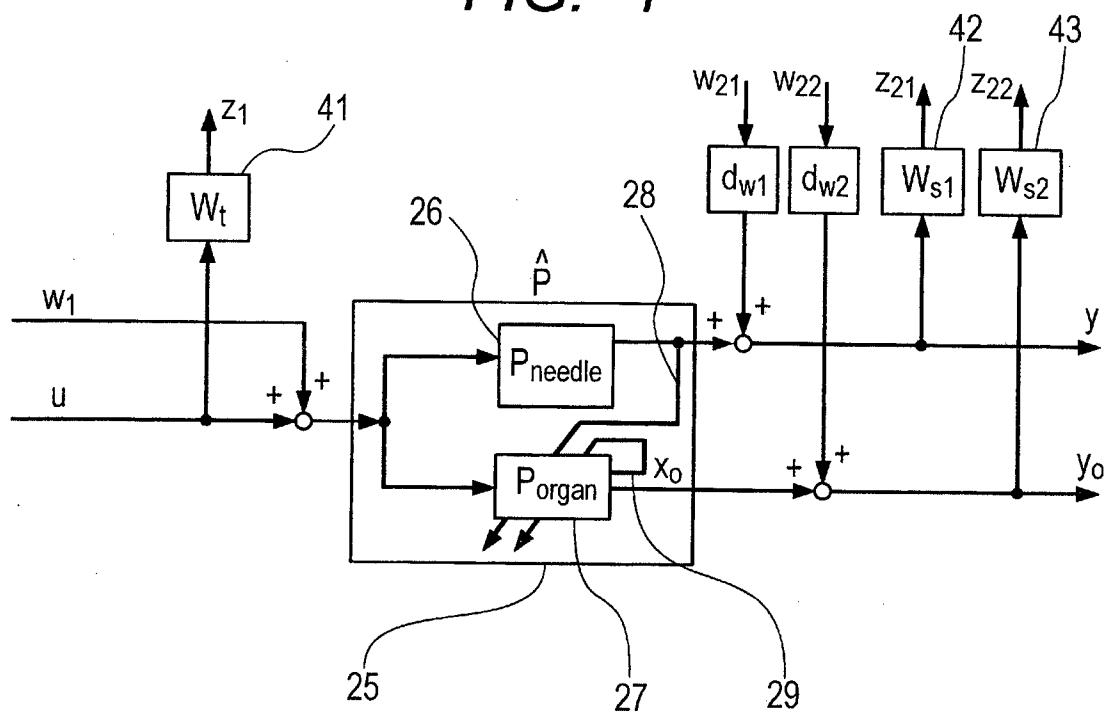
FIG. 5
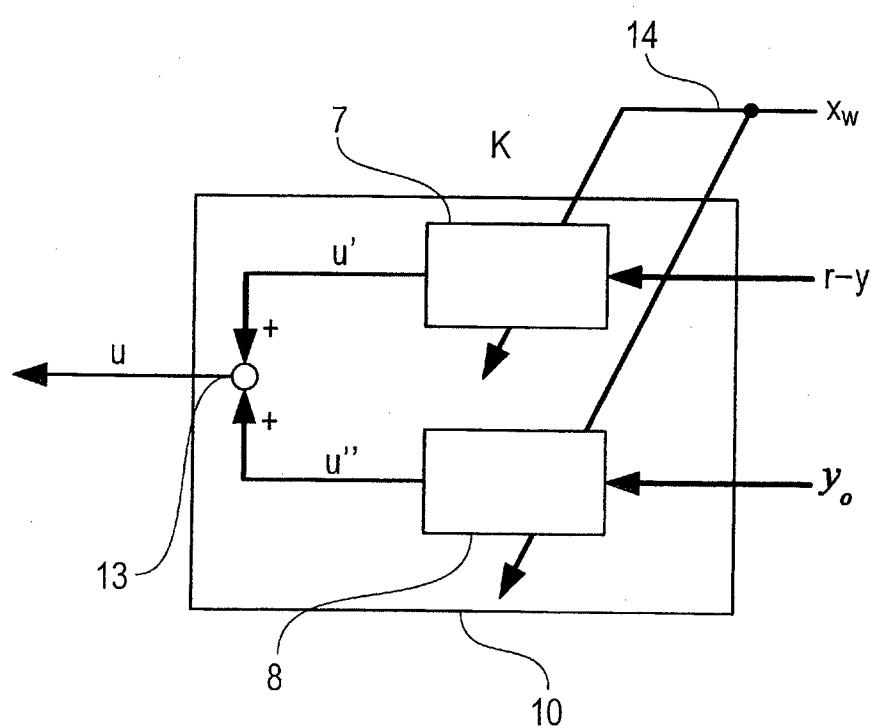
FIG. 6A
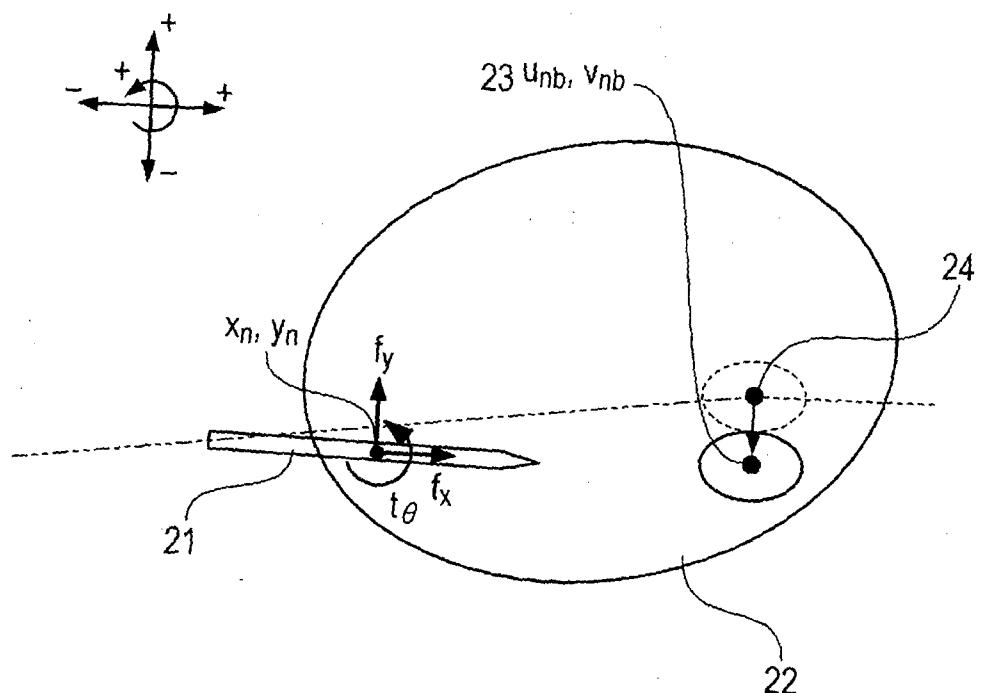
FIG. 6B
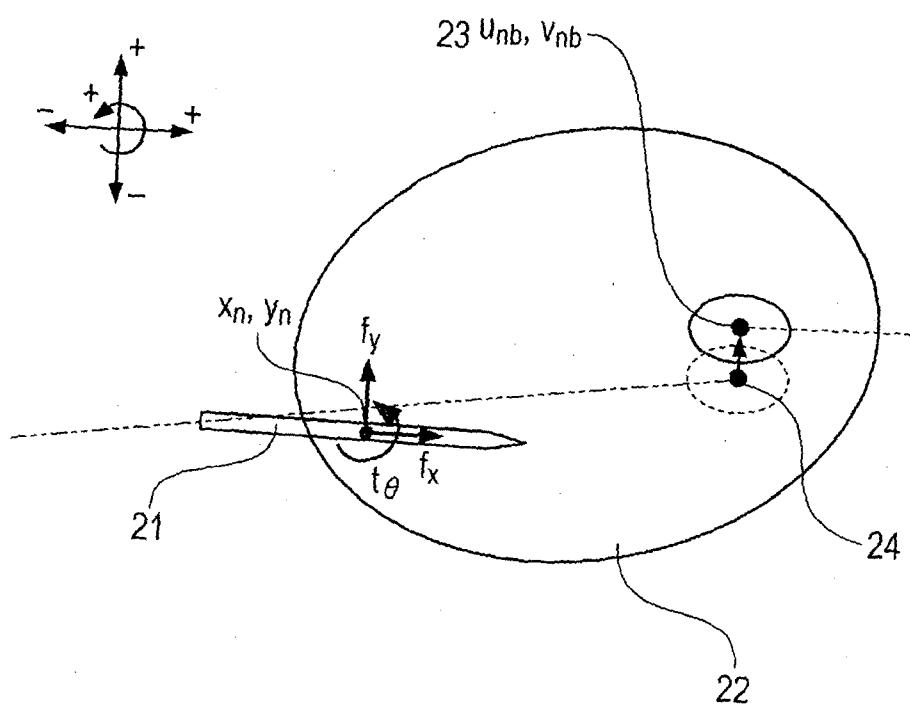
FIG. 7
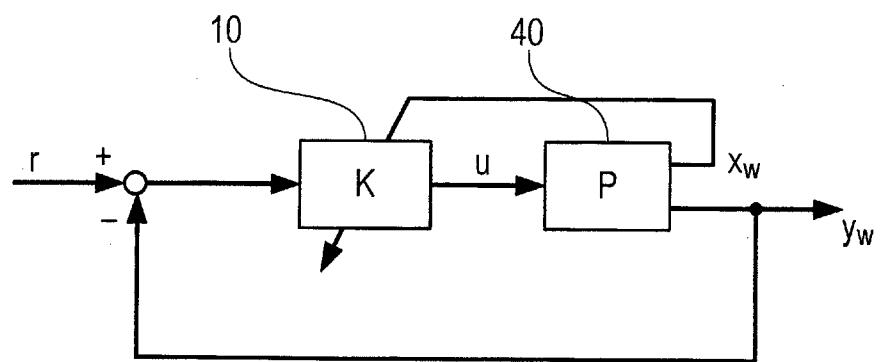
FIG. 8
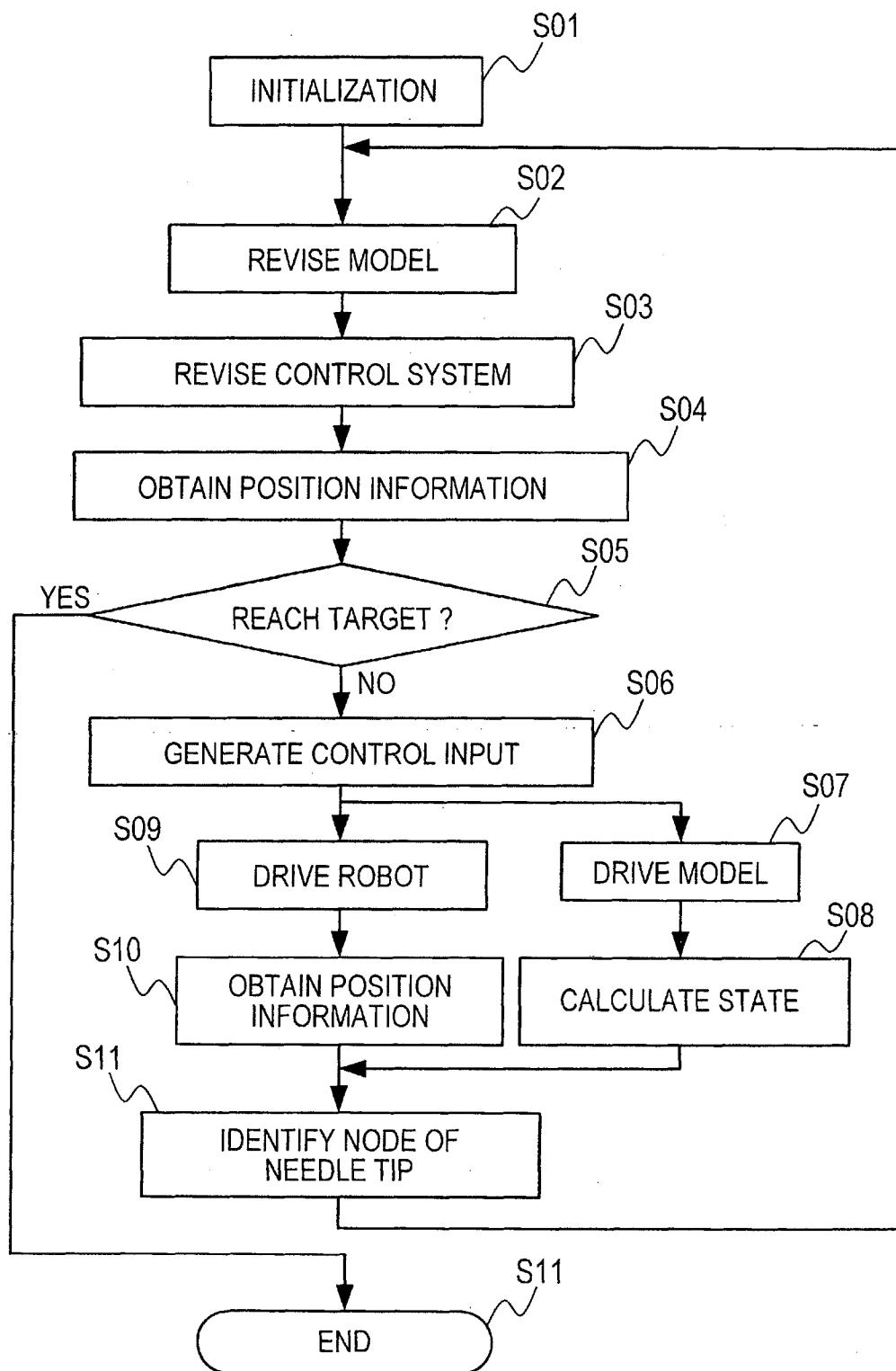
FIG. 9A

FIG. 9B

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
INV. A61B19/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2007/141784 A2 (TECHNION RES & DEV FOUND LTD) 13 December 2007 (2007-12-13) pages 15,18,19; figures 9A,10	1-4
X	US 2007/016067 A1 (WEBSTER ROBERT J III [US] ET AL WEBSTER III ROBERT J [US] ET AL) 18 January 2007 (2007-01-18) paragraphs [0043], [0057] - [0069]; figure 2	1-4
X	JP 2006 271546 A (UNIV WASEDA) 12 October 2006 (2006-10-12) cited in the application the whole document; figure 1	1-4
A	EP 1 905 377 A1 (BRAINLAB AG [DE]) 2 April 2008 (2008-04-02) abstract	1

-/--

[X] Further documents are listed in the continuation of Box C.　　[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
7 November 2013	15/11/2013

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Mayer-Martenson, E

Form PCT/ISA/210 (second sheet) (April 2005)

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	Daniel Glozman ET AL: "Flexible Needle Steering and Optimal Trajectory Planning for Percutaneous Therapies", 1 January 2004 (2004-01-01), XP055053435, Retrieved from the Internet: URL:http://download.springer.com/static/pd f/295/chp%3A10.1007%2F978-3-540-30136-3_18 .pdf?auth66=1362141539_b4c7e9e27c9e72c5eac 0d7915de378d5&ext=.pdf [retrieved on 2013-02-14] the whole document -----	1-4
A	US 2011/270270 A1 (VANCAMBERG LAURENCE [FR] ET AL) 3 November 2011 (2011-11-03) abstract -----	1-4

1

Form PCT/ISA/210 (continuation of second sheet) (April 2005)

| Box No. II | Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet) |

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. [X] Claims Nos.: 5, 6
because they relate to subject matter not required to be searched by this Authority, namely:

Rule 39.1(iv) PCT - Method for treatment of the human or animal body by surgery

2. [ ] Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. [ ] Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

| Box No. III | Observations where unity of invention is lacking (Continuation of item 3 of first sheet) |

This International Searching Authority found multiple inventions in this international application, as follows:

1. [ ] As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. [ ] As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.

3. [ ] As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. [ ] No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest
[ ] The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

[ ] The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

[ ] No protest accompanied the payment of additional search fees.

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
WO 2007141784	A2	13-12-2007	CA	2654343 A1	13-12-2007
			CN	101522134 A	02-09-2009
			EP	2029035 A2	04-03-2009
			JP	5103658 B2	19-12-2012
			JP	2010506600 A	04-03-2010
			US	2009149867 A1	11-06-2009
			WO	2007141784 A2	13-12-2007
US 2007016067	A1	18-01-2007	NONE		
JP 2006271546	A	12-10-2006	JP	4390146 B2	24-12-2009
			JP	2006271546 A	12-10-2006
EP 1905377	A1	02-04-2008	EP	1905377 A1	02-04-2008
			US	2008082110 A1	03-04-2008
US 2011270270	A1	03-11-2011	FR	2959409 A1	04-11-2011
			JP	2011235089 A	24-11-2011
			US	2011270270 A1	03-11-2011