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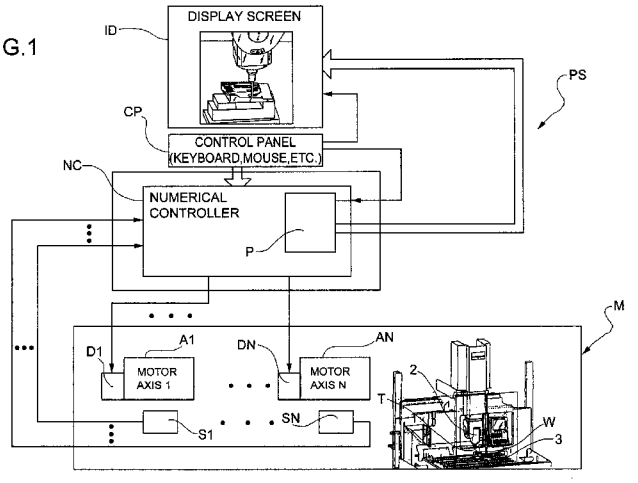
[Continued on next page]

(54) **Title**: A PREDICTIVE CONTROL AND VIRTUAL DISPLAY SYSTEM FOR A NUMERICALLY CONTROLLED MACHINE TOOL

FIG.1



(57) **Abstract**: The system performs control and virtual display (1) for a machine tool (M) which comprises a tool-holder (2) for a tool (T), a carrier (3) for a workpiece (W) to be machined by means of the tool (T), and a plurality of actuator devices (Al,..., AN) which can be controlled by means of associated drivers (D1,..., DN) in order to bring about controlled relative displacements between the tool (T) and the workpiece (W) along respective axes. The control system (1) comprises: a numerical controller (NC) which is connected to the drivers (D1,..., DN) and is suitable for implementing a machining program that is predetermined according to the features of the workpiece (W) to be produced and the features of the tool (T); the numerical controller (NC) is suitable for calculating, on the basis of the machining program, target coordinates defining positions of the tool (T) along the axes, which positions are to be reached by the activation of the associated actuator devices (Al, AN); image display means (ID); and a processing system (P) which is incorporated in and/or connected to the numerical controller (NC) in order to receive the calculated target coordinate values, and which is arranged to generate, on the basis of the target coordinates and of stored mathematical models of the machine (M), of the workpiece and of the tool, image data suitable for producing on the image display means (ID) a predictive, virtual, two-dimensional representation of the positions adopted by the workpiece (W) and by the tool (T) up to a preselected future moment.

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SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

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— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *of inventorship (Rule 4.17(iv))*

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))*

A predictive control and virtual display system for a numerically controlled machine tool

The present invention relates in general to the field of numerically controlled machine tools.

More specifically, the subject of the present invention is a control system for a machine tool which comprises, in known manner:

a holder for a tool,

a carrier for a workpiece to be machined by the tool, and

a plurality of actuator devices which can be controlled by associated drive means in order to bring about controlled relative displacements between the tool and the workpiece along respective axes;

the control system comprising:

a numerical controller which is connected to the drive means and is suitable for implementing a machining program that is predetermined according to the features of the workpiece to be produced and to the features of the tool used; the numerical controller being suitable for calculating, on the basis of the machining program, target coordinate values defining positions of the tool along the axes, which positions are to be reached by the activation of the associated actuator devices.

There are known control systems for machine tools which also have image display devices and which permit the real-time display of real or virtual images that show the workpiece and the tool in their instantaneous positions.

A control system of this type is described, for example, in US patent 6,546,127 B1.

A control and display system for a numerically controlled machine tool is also known from US patent application 2010/00063616 A1; in this system real images obtained by means of one or more video cameras, or virtual images obtained by calculation means are displayed, selectively. Real images are displayed when no cooling liquid is being supplied into the working zone of the machine whereas virtual images are displayed when the supply of cooling liquid is in progress.

Known control and display systems in any case permit purely the display of real or virtual images of what is happening in the work zone at the time in question.

An object of the present invention is to provide an improved control and display system which permits a preliminary graphic examination of the movements which will be performed by the machine tool as soon as the operator imparts the command to start the machining program.

Systems for simulating machining programs are also known; these validate the paths of the tools before they are sent to the machine. In many fields, for example in the machining of moulds, the machine operator often introduces into the numerical controller transformations to be applied to the machining program (for example, translations, rotations, scale factors, corrections of the radius of the tool, etc.) which, naturally, cannot be checked by the simulation systems.

An object of the present invention is therefore to display the movements of the axes of the machine tool "downstream" of all of the transformations set by the operator and to enable them to be checked graphically before being executed in the machine to allow any potential error to be detected and hence to prevent damage to the tool, to the workpiece, or to the machine.

These and other objects are achieved, according to the invention, by a control system of the type defined above, further comprising:

image display means, and

a processing system which is incorporated in and/or connected to the numerical controller in order to receive the calculated target coordinate values, and which is arranged to generate, on the basis of the target coordinates and of stored mathematical models of the workpiece, of the tool, of the clamping arrangements, and of the machine tool itself, image data suitable for producing on the display means a predictive, virtual, two-dimensional representation of the positions which will be adopted by the workpiece and by the tool, up to a preselected future moment.

The operator of the machine tool can thus define a "window" for the checking and display of the movements which will be performed at subsequent times by setting the number of "execution blocks" or the amount of space (distance travelled) which the system will have to display and check in advance. This concept will be referred to below by the term "predictive window".

"Execution block" means the elemental execution unit of a machining program. A machining program is essentially a file constituted mainly by a series of instructions for movement of the axes, each of which translates into a series of elemental movements (or execution blocks) of the machine tool.

By virtue of these features, the control and virtual display system according to the invention enables, for example, problems or dangerous situations such as future possible collisions of the tool with parts of the machine, or of parts of the machine against the workpiece, and excessive removals of material from the workpiece, to be checked visually in advance. The system can also be rendered capable of stopping the execution of the machining on the machine tool, when it is enabled to detect the above-mentioned dangerous situations in advance.

Further characteristics and advantages of the invention will become clear from the following detailed description which is given purely by way of non-limiting example with reference to the appended drawings, in which:

Figures 1 and 2 are block diagrams of two embodiments of a control and virtual display system for a machine tool according to the present invention;

Figure 3 is a flow chart illustrating the method of operation of a control and virtual display system according to the present invention, and

Figure 4 shows an example of a virtual image formed in a system according to the present invention.

Figure 1 shows partially and schematically a machine tool M which is associated with a predictive control and virtual display system according to the invention, generally indicated PS.

The machine tool M comprises, in known manner, a tool-holder 2 which carries, for example, a milling tool T.

The machine tool M comprises, in known manner, a housing, a support structure, and a table.

The machine M further comprises a workpiece carrier 3 which carries a workpiece W to be machined and which can normally be "updated" dynamically during the machining.

A plurality of actuator devices A1, ..., AN, for example, electric motors, are provided in the machine M and can be controlled by means of associated drive devices D1, ..., DN in order to bring about controlled relative displacements between the tool T and the workpiece W being machined, along respective axes.

Respective detector devices S1, ..., SN suitable for providing respective electrical signals or position data are associated with the actuators A1, ..., AN.

A numerical controller NC is associated with the machine tool M. The numerical controller NC is connected to the drive devices D1, ..., DN and is arranged to implement a machining program which is predetermined according to the features of the workpiece to be produced and to the features of the machine tool M and of the tool T which are used. In particular, the numerical controller NC can calculate, on the basis of the machining program, the target coordinate values which define positions of the tool T along the axes of the machine M, which positions are to be reached by the activation of the associated actuator devices A1, ..., AN.

The operator of the machine M can interact with the numerical controller NC by means of a control panel CP.

In the embodiment shown in Figure 1, the predictive control system PS shares with the numerical controller NC an image display device ID and the or a module P of the numerical controller NC which uses the calculated target coordinate values. On the basis of

these values, as well as of stored mathematical models of the workpiece W, of the machine M, and of the tool T, the module P generates image data signals which it supplies to the display device ID.

The control system PS is arranged in particular to generate image signals which enable a two-dimensional, virtual representation of the relative positions adopted by the machine M and by the workpiece W to be produced on the display device ID.

In particular, the control system PS is arranged to generate images which can selectively permit the production of:

- an instantaneous, virtual, two-dimensional representation of the current positions of the workpiece W and of the tool T in real time; this representation in practice replaces the images which could be obtained, for example, by means of a video camera to show the operator what is happening at the time in question in the work zone of the machine tool M; or
- a predictive, virtual, two-dimensional representation of the positions adopted by the workpiece W, by the tool T and by the machine tool M from the start of the machining up to the end of the "predictive window" set by the operator of the machine M, for example, by means of the control panel CP.

The above-mentioned representations are advantageously produced on the basis of the target coordinate values calculated by the numerical controller NC and of the mathematic models of the machine tool M, of the tool-holder, of the tool T, of the clamping apparatus, of the dynamic unfinished workpiece, and of any theoretical model of the workpiece to be achieved upon completion of the machining.

Figure 2 shows another embodiment of the present invention. In this drawing parts and components that have already been described have again been attributed the alphanumeric references which were used above.

In the embodiment of Figure 2, the predictive control and display system PS comprises its own control panel (keyboard and/or mouse, etc.) CP1, its own processor P, and its own

display device ID1, which are separate from those (CP and ID) associated with the numerical controller NC.

Otherwise, the features and methods of operation of the system of Figure 2 correspond to those already described with reference to the system of Figure 1.

Figure 4 shows, by way of example, a virtual, two-dimensional image which can correspondingly be presented on the display device ID; in this image, the alphanumeric symbols used above to distinguish the various parts have been added for ease of identification by the reader.

When the system is in use, the following sequence of steps can take place:

a) the operator of the machine tool selects the machining program;
b) the operator defines the "predictive window";
c) the operator can display the virtual movements of the machine and of the tool to check the correctness of the machining program by displaying the position of the tool forward and backward within the "predictive window";
d) the operator presses the start key and sets the speed of advance; the numerical controller brings about the movement of the axes of the machine in accordance with the machining program selected;
e) the operator of the machine tool can display the position of the tool and the axes of the machine relative to the workpiece in advance and according to the defined extent of the "predictive window"; and
f) if the operator wishes to make other checks he brings the value of the speed of advance to zero or stops the machine and the system returns to point c).

Figure 3 of the appended drawings shows a possible simplified flow chart of the steps which can be performed with the predictive control and virtual display system described above.

In Figure 3, the step for starting operation is indicated 10 and is followed by a step 11 for

the reading, by the numerical controller NC, of the previously stored machining program, or for the acquisition of the manual commands imparted by the machine operator by means of the control panel CP.

There then follows a step 12 for checking whether the machining program is completed; if so, the process goes to an end step 13 whereas, if not, it goes to a step 25 in which it is checked whether the start command and the speed of advance are other than zero, or whether the operator has changed the amplitude of the "predictive window". If not, the system returns to step 12; if so, it goes to a step 14 in which the numerical controller NC provides for the calculation of the target coordinates for the various axes of the machine tool M in the "predictive window" set by the operator.

This step is followed by a step 26 for checking of the start command and of the speed of advance; if they are zero the system returns to step 12, otherwise it goes to a step 15 for operation of the actuators A1, ..., AN associated with the axes in order to reach the positions indicated by the target coordinates. There then follow a step 16 for the acquisition of the position signals provided by the detectors S1, ..., SN associated with the axes and a step 17 in which the actual positions indicated by the detectors S1, ..., SN are compared with the corresponding target coordinate values.

The differences between the actual positions and the target coordinates, or position errors, are used for the feedback "adjustment" of the actuators A1, ..., N associated with the axes of the machine tool M.

As a result of the starting of the process described above, in a step indicated 18 in the representation of Figure 3, it is checked whether the user has requested the production of a virtual display of the machining in progress in the machine M. If so the system goes on to a step 19 in which the target coordinates calculated little by little by the numerical controller NC are acquired by the processing system PS.

In a subsequent step 20, it is checked whether the user has requested the generation of a virtual display, in real time, of what is happening at present in the work zone of the

machine tool M. If so, the processing system PS processes the virtual, two-dimensional images in the next step 21 and these are then presented to the user on the display device ID in step 22.

If, on the other hand, in step 20, the user has not requested the virtual representation of the instantaneous work situation in real time, then the system can go on to step 23 in which a predictive, virtual, two-dimensional representation of the positions adopted by the machine M, by the workpiece W, and by the tool T from the start of the work and up to the end of the "predictive window" set by the operator is generated.

The end of the "predictive window" can be set by the operator by the indication of the corresponding number of program "blocks" corresponding to the future time window of interest or by indication of the distance to be travelled by the tool T, as indicated in step 24.

The processor then proceeds cyclically in accordance with the steps or stages indicated above.

The system PS can be arranged so that, during the normal carrying-out of a machining program, the virtual image corresponding to the end of the "predictive window" set is presented little by little on the display device ID.

The processing system PS can advantageously be arranged to check whether the calculated future positions of the tool T are liable to lead to any dangerous collisions with parts of the machine tool M or with the workpiece W and possibly to bring about the emission of an alarm signal and/or stoppage of the machining.

The processing system PS can also advantageously be arranged to calculate the following quantities:

- the total amount of material to be removed from the workpiece W being machined;
- the total remaining amount still to be removed from the workpiece W, and
- any excessive removals of material from the workpiece W, and
- to calculate and adjust the speed of advance of the tool T on the basis of the volume

of material removed from the workpiece W, of the nature of the material, of the kind of tool T used, and of the features of the machine tool M, and to estimate the remaining useful life of the tool T on the basis of these parameters.

Naturally, the principle of the invention remaining the same, the forms of embodiment and details of construction may be varied widely with respect to those described and illustrated purely by way of non-limiting example, without thereby departing from the scope of the invention as defined in the appended claims.

CLAIMS

1. A control and virtual display system (PS) for use whilst machining is in progress in a machine tool (M) which comprises:

a holder (2) for a tool (T),

a carrier (3) for a workpiece (W) to be machined by means of the tool (T), and

a plurality of actuator devices (A1, ..., AN), which can be controlled by associated drive means (D1, ..., DN) in order to bring about controlled relative displacements between the tool (T) and the workpiece (W) along respective axes;

there being associated with the machine tool (M):

a numerical controller (NC) which is connected to the drive means (D1, ..., DN) and is suitable for implementing a machining program that is predetermined according to the features of the workpiece (W) to be produced and the features of the tool (T); the numerical controller (NC) being suitable for calculating, on the basis of the machining program, target coordinates defining positions of the tool (T) along the axes, which positions are to be reached by the activation of the associated actuator devices (A1, ..., AN); and

image display means (ID);

the system (PS) being characterized in that it comprises a processing system (P) which is incorporated in and/or connected to the numerical controller (NC) in order to receive the calculated target coordinate values, and which is arranged to generate, whilst machining is in progress and on the basis of the target coordinates and of stored mathematical models of the machine (M), of the workpiece (W), and of the tool (T), image data suitable for producing on the image display means (ID) a virtual, two-dimensional representation of the positions which will be adopted by the workpiece (W) and by the machine (M) in a pre-set "predictive time window".

2. A control and virtual display system according to claim 1, wherein the processing system (P) is arranged for selectively generating image data suitable for producing, on the image display means (ID), an instantaneous, virtual, two-dimensional representation, in real time, of the current positions of the workpiece (W) and of the tool (T).

3. A system according to claim 1 or 2, comprising setting means (CP) allowing the extent of the desired "predictive window" to be selected.

4. A system according to any of the preceding claims, wherein the processing system (P) is arranged to check whether the calculated future positions of the tool (T) are liable to cause possible collisions.

5. A system according to claim 4, wherein the processing system (P) is arranged to cause the emission of an alarm signal and/or to cause the machining to be stopped when the calculated future positions of the tool (T) are liable to cause possible collisions.

6. A system according to any of the preceding claims, wherein the processing system (P) is arranged to calculate the total amount of material to be removed from the workpiece (W) in the display "predictive window" set, and/or the total remaining amount of material still to be removed from the workpiece (W) up to the completion of the machining within the "predictive window" set.

7. A system according to any of the preceding claims, wherein the processing system (P) is arranged to calculate predictively possible future excessive removals of material from the workpiece (W).

8. A system according to any of the preceding claims, wherein the processing system (P) is arranged to calculate and adjust the speed of advance of the tool (T) on the basis of the volume of material removed from the workpiece (W), of the nature of the material, of the kind of tool used, and of the features of the machine tool (M).

9. A system according to any of the preceding claims, wherein the processing system (P) is arranged to bring about, whilst a machining program is being carried out, the presentation, little by little on the image display means (ID), of a virtual image corresponding to the end of the "predictive window" set.

10. A system according to claim 9, wherein the processing system (P) is arranged to estimate the remaining useful life of the tool (T).

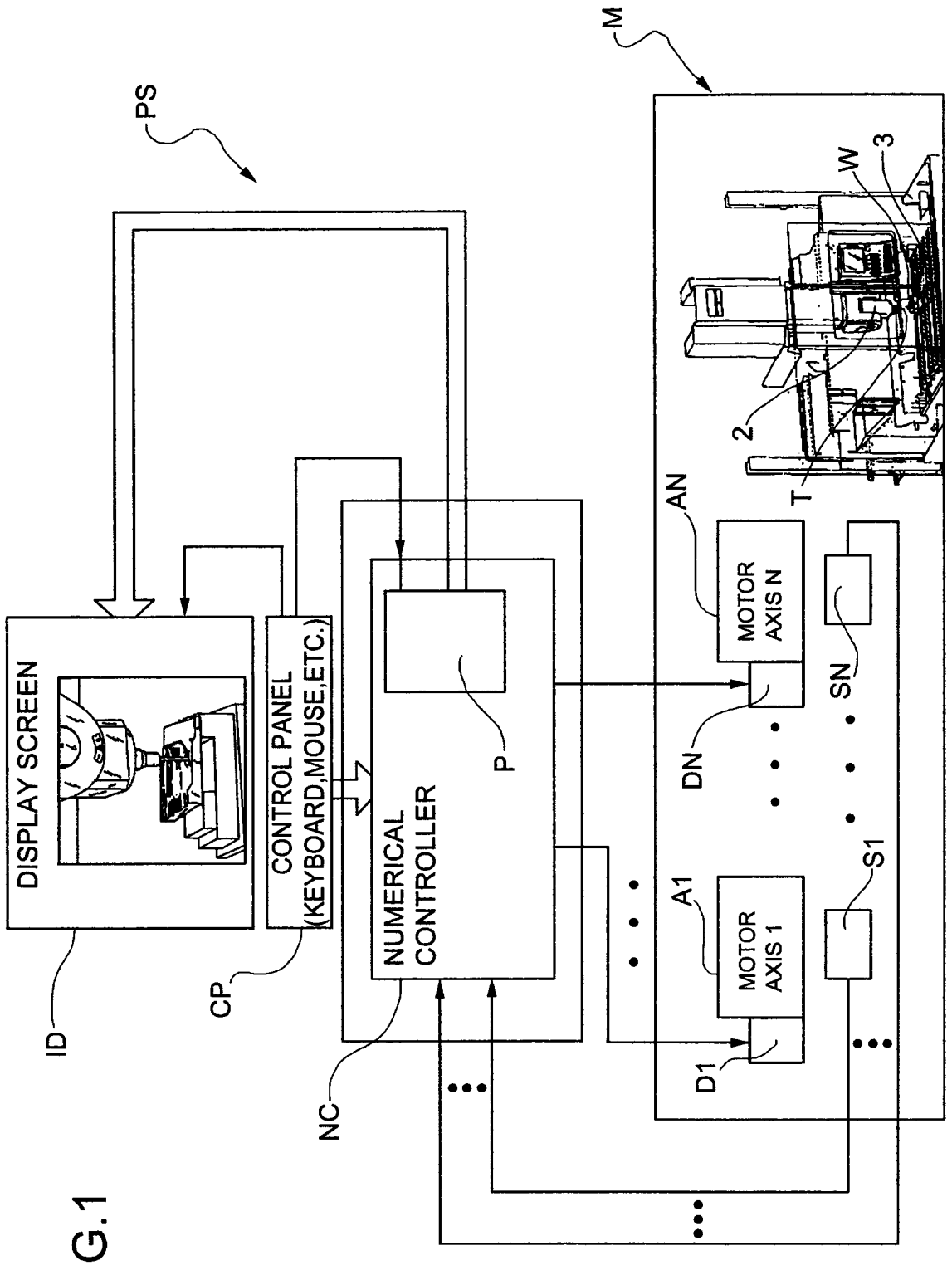
PS
M
W
3
2
T
AN
MOTOR AXIS N
SN
DN
P
DISPLAY SCREEN
CONTROL PANEL (KEYBOARD,MOUSE,ETC.)
NUMERICAL CONTROLLER
A1
MOTOR AXIS 1
S1
D1
ID
CP
NC

FIG.1

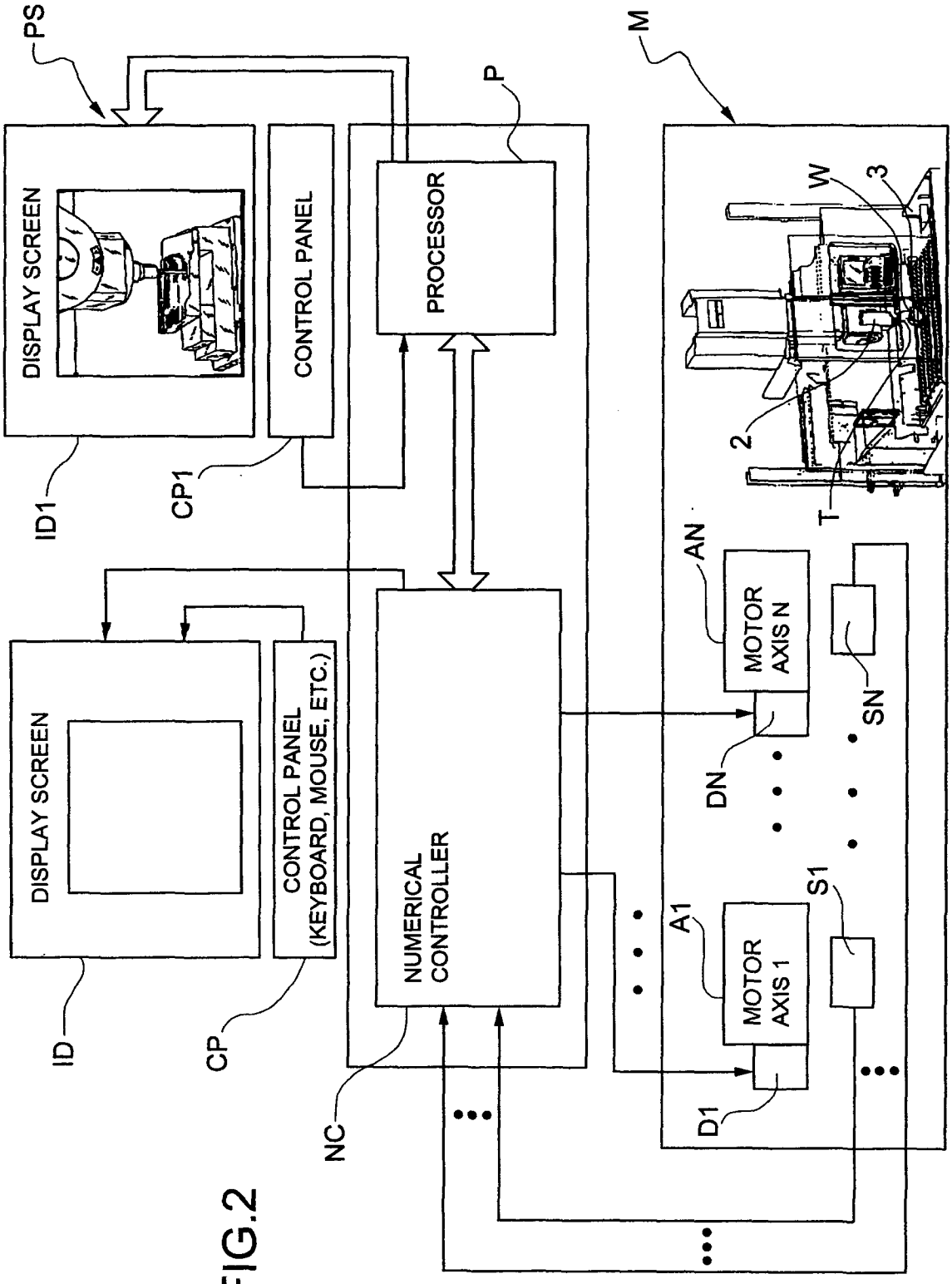
PS
DISPLAY SCREEN
CONTROL PANEL
PROCESSOR
P
M
W
3
2
T
ID1
CP1
AN
MOTOR AXIS N
SN
DN
DISPLAY SCREEN
CONTROL PANEL (KEYBOARD, MOUSE, ETC.)
NUMERICAL CONTROLLER
A1
MOTOR AXIS 1
S1
D1
ID
CP
NC

FIG.2

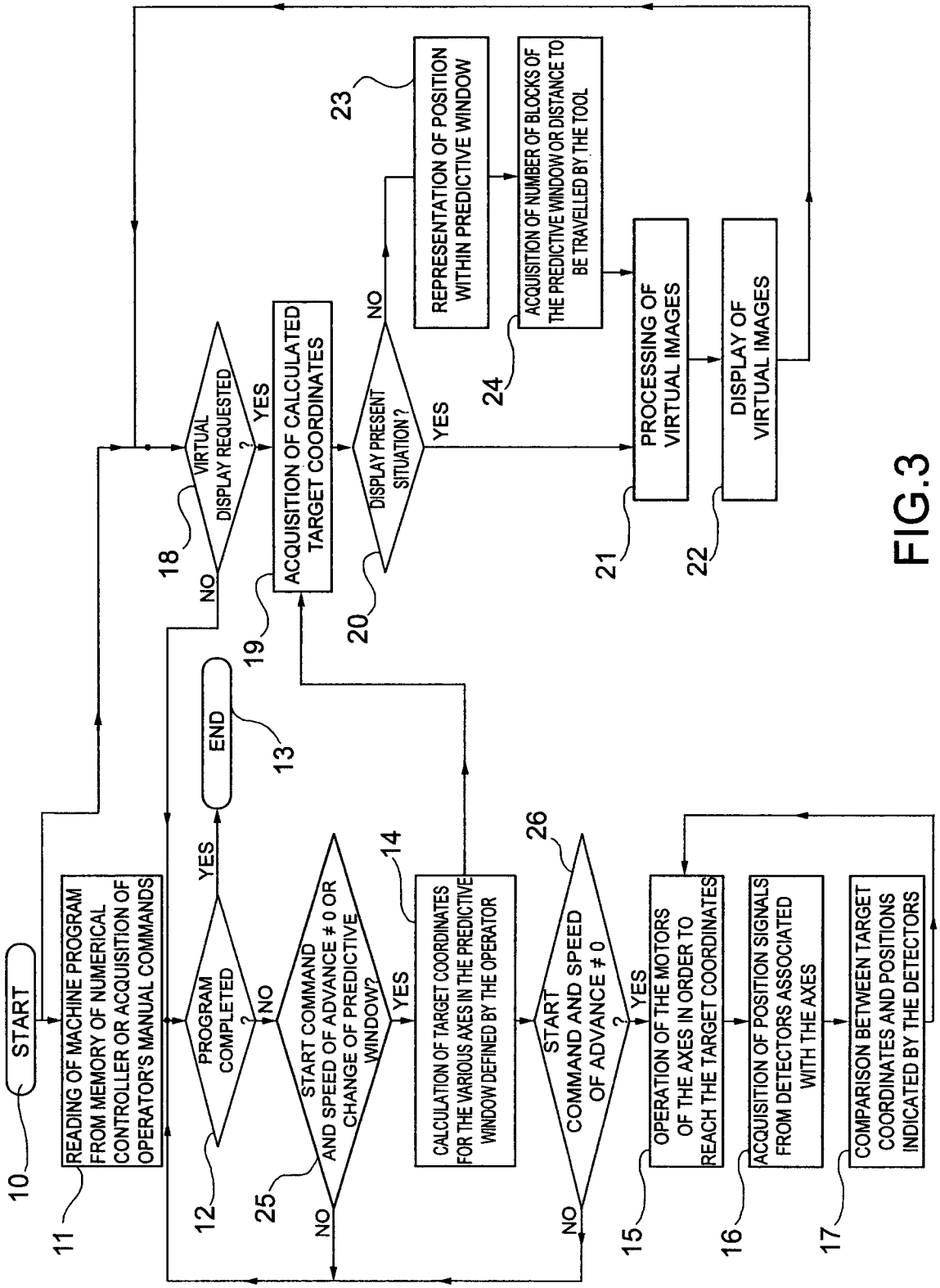
START
10
READING OF MACHINE PROGRAM FROM MEMORY OF NUMERICAL CONTROLLER OR ACQUISITION OF OPERATOR'S MANUAL COMMANDS
11
PROGRAM COMPLETED ?
12
YES
END
13
NO
START COMMAND AND SPEED OF ADVANCE ≠ 0 OR CHANGE OF PREDICTIVE WINDOW?
25
YES
CALCULATION OF TARGET COORDINATES FOR THE VARIOUS AXES IN THE PREDICTIVE WINDOW DEFINED BY THE OPERATOR
14
NO
START COMMAND AND SPEED OF ADVANCE ≠ 0 ?
26
YES
OPERATION OF THE MOTORS OF THE AXES IN ORDER TO REACH THE TARGET COORDINATES
15
ACQUISITION OF POSITION SIGNALS FROM DETECTORS ASSOCIATED WITH THE AXES
16
COMPARISON BETWEEN TARGET COORDINATES AND POSITIONS INDICATED BY THE DETECTORS
17
NO
VIRTUAL DISPLAY REQUESTED ?
18
YES
ACQUISITION OF CALCULATED TARGET COORDINATES
19
DISPLAY PRESENT SITUATION ?
20
NO
REPRESENTATION OF POSITION WITHIN PREDICTIVE WINDOW
23
ACQUISITION OF NUMBER OF BLOCKS OF THE PREDICTIVE WINDOW OR DISTANCE TO BE TRAVELLED BY THE TOOL
24
YES
PROCESSING OF VIRTUAL IMAGES
21
DISPLAY OF VIRTUAL IMAGES
22

FIG.3

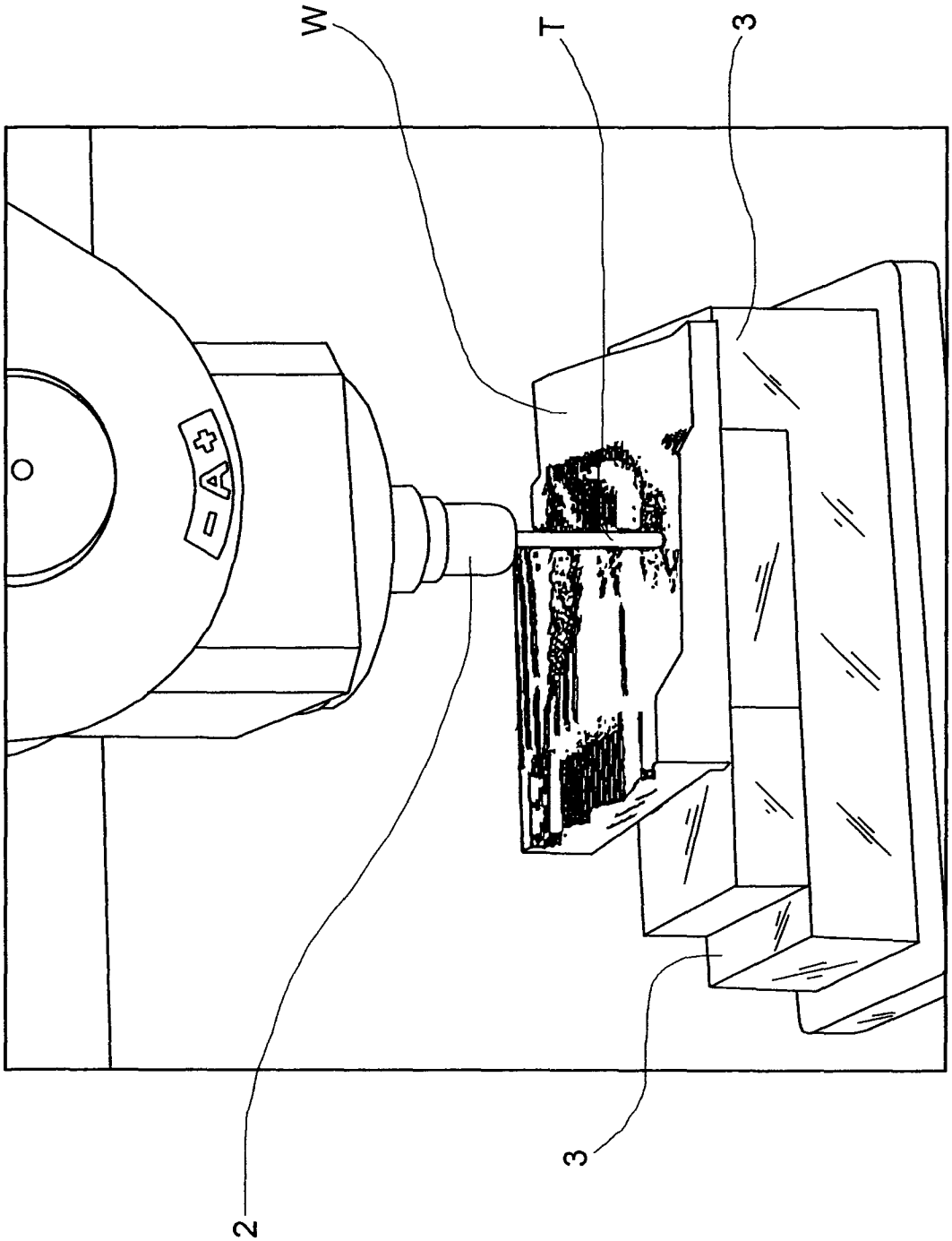

FIG.4

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2011/053512

A. CLASSIFICATION OF SUBJECT MATTER
INV. G05B19/4069
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)
G05B

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 practical, search terms used)
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2005/102054 A1 (DOLANSKY STEFAN [DE]) 12 May 2005 (2005-05-12)	1,3-10
Y	page 1 - page 4 figures 1, 2A	2

X	WO 2009/158559 A1 (SIEMENS PRODUCT LIFECYCLE MAN [US]; LIN GEN SHIENG [US]) 30 December 2009 (2009-12-30)	1,3-10
Y	paragraph [0001] - paragraph [0045] paragraph [0074] - paragraph [0077]	2

Y	US 6 546 127 B1 (SEONG DAE JUNG [KR] ET AL) 8 April 2003 (2003-04-08) cited in the application	2
A	column 1 - column 2	1,3-10

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[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

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"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
1 December 2011	08/12/2011

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	Bassi, Luca

1

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

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2011/053512

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2010/063616 A1 (MORI MASAHIKO [JP] ET AL) 11 March 2010 (2010-03-11) cited in the application	2
A	page 1 - page 2	1,3-10

A	US 2002/164221 A1 (IZUTSU YUKIO [JP] ET AL) 7 November 2002 (2002-11-07) the whole document	6-10

A	WO 03/019454 A1 (SURFWARE INC [US]) 6 March 2003 (2003-03-06) the whole document	6-10

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IB2011/053512

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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