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(54) **ROBOT VEHICLE ADAPTED TO OPERATE IN PIPELINES AND OTHER NARROW PASSAGES**

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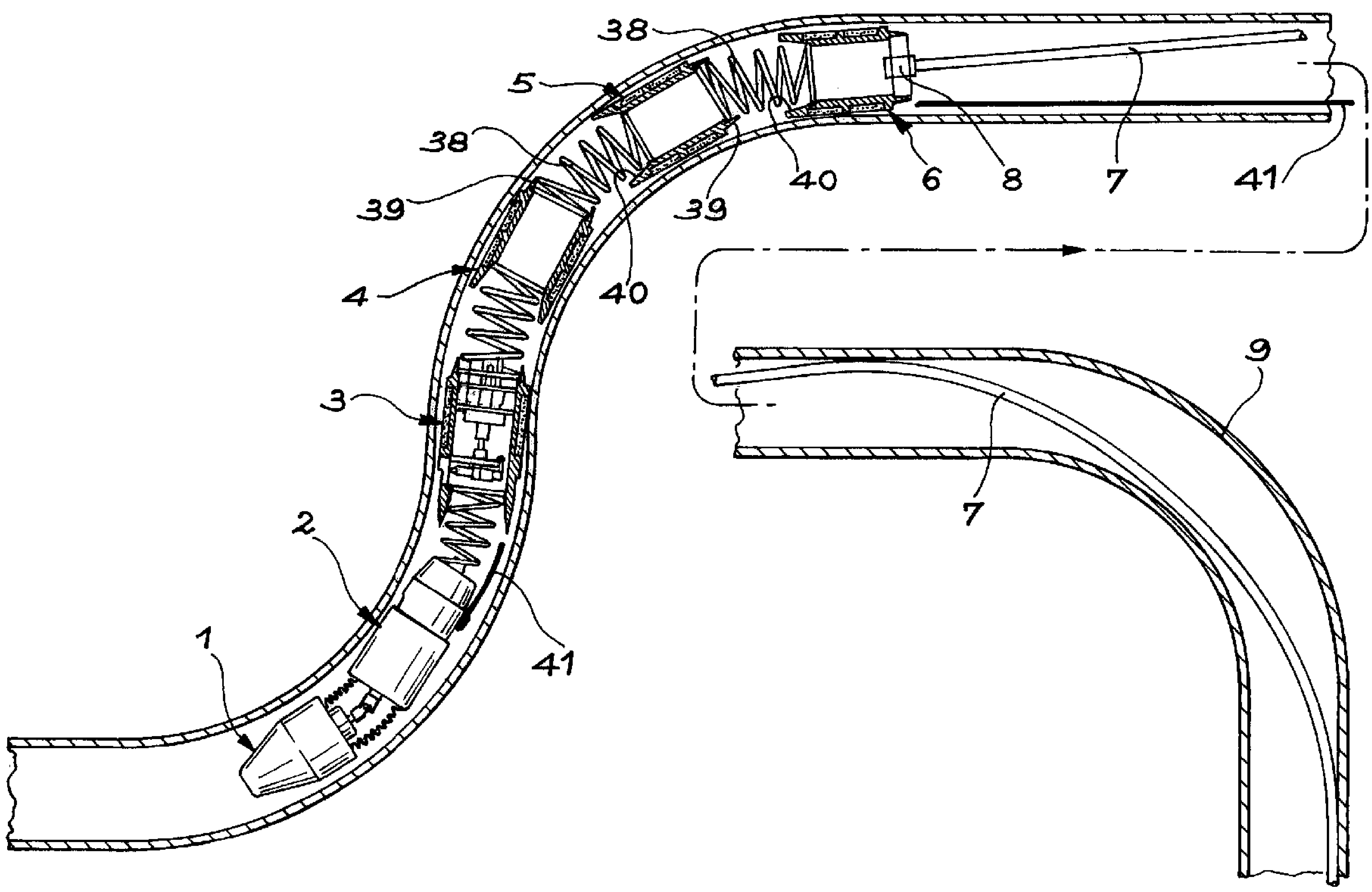
(57) **ABSTRACT**

The train (**1**) of modules (**2** to **6**) that forms the robot comprises springs (**38**) to connect the successive modules together enabling curvature of the train in the bends of a pipe. However, cables (**41**) bring the modules together by compressing the springs when they are pulled, until the conical end faces (**39, 40**) are engaged in each other; the train is made rigid and can be immobilised inside the pipe to perform different types of machining operations, including welding or cutting joints between successive pipes in the pipework.



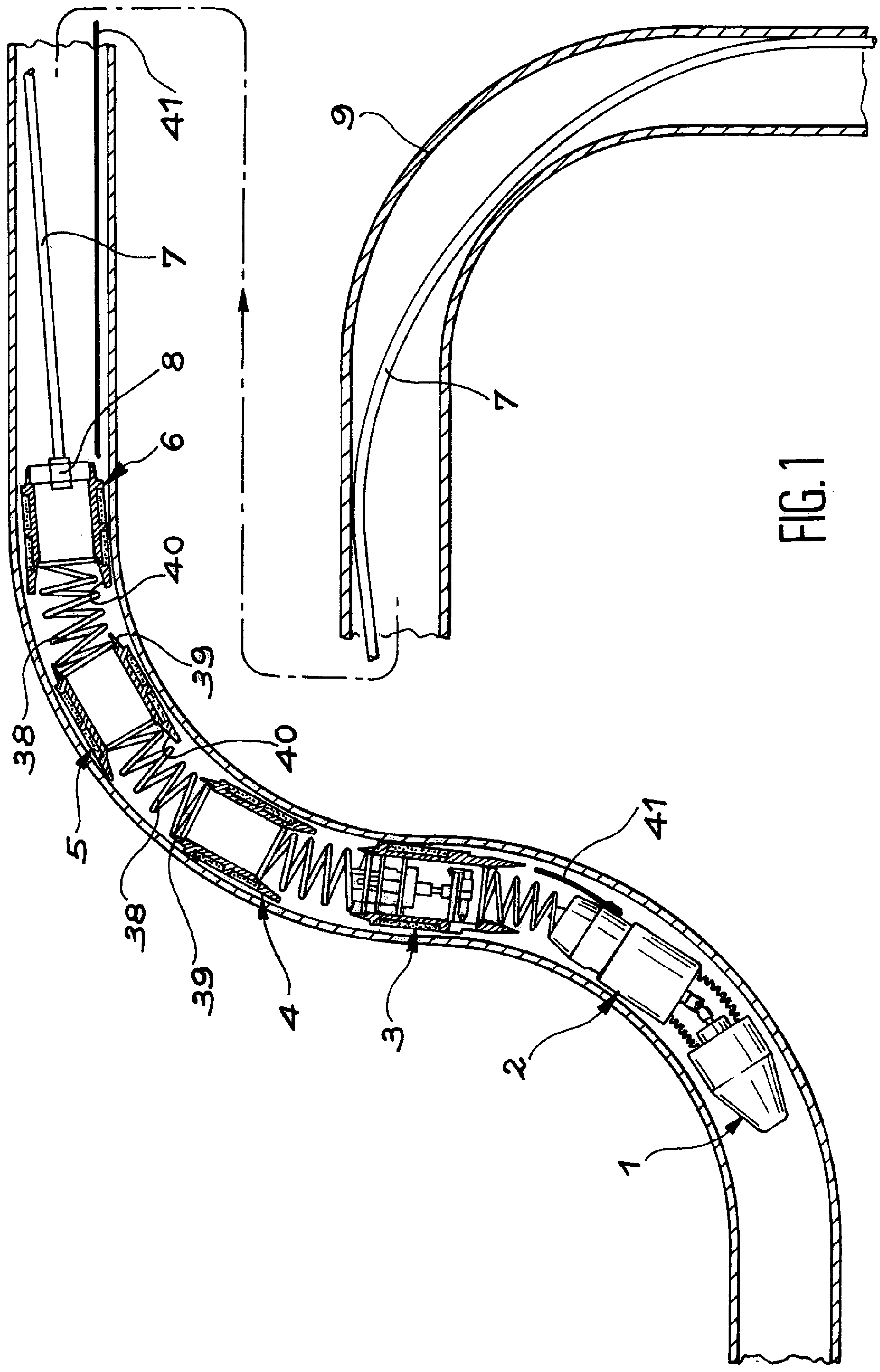


FIG.1

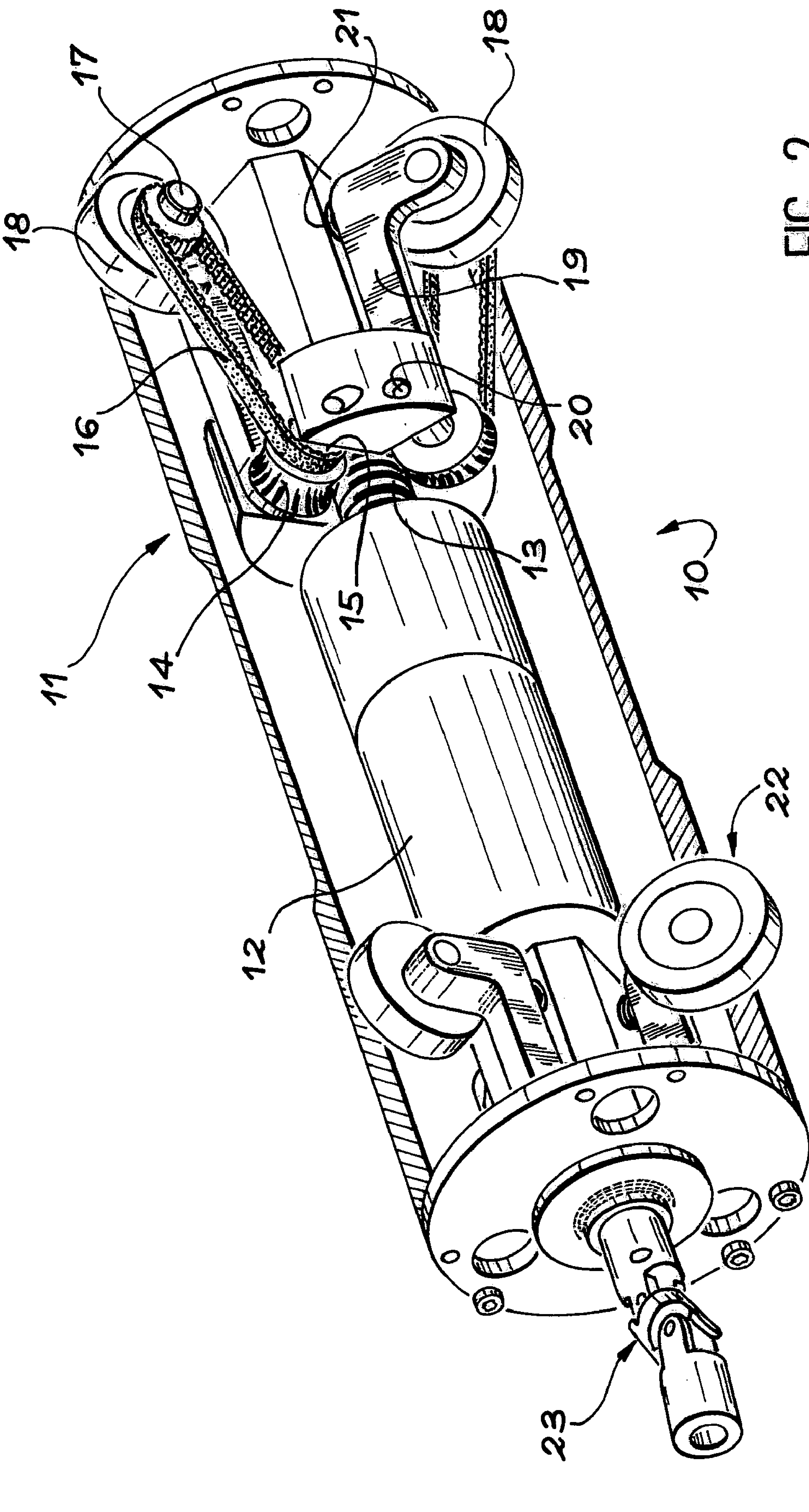


FIG. 2

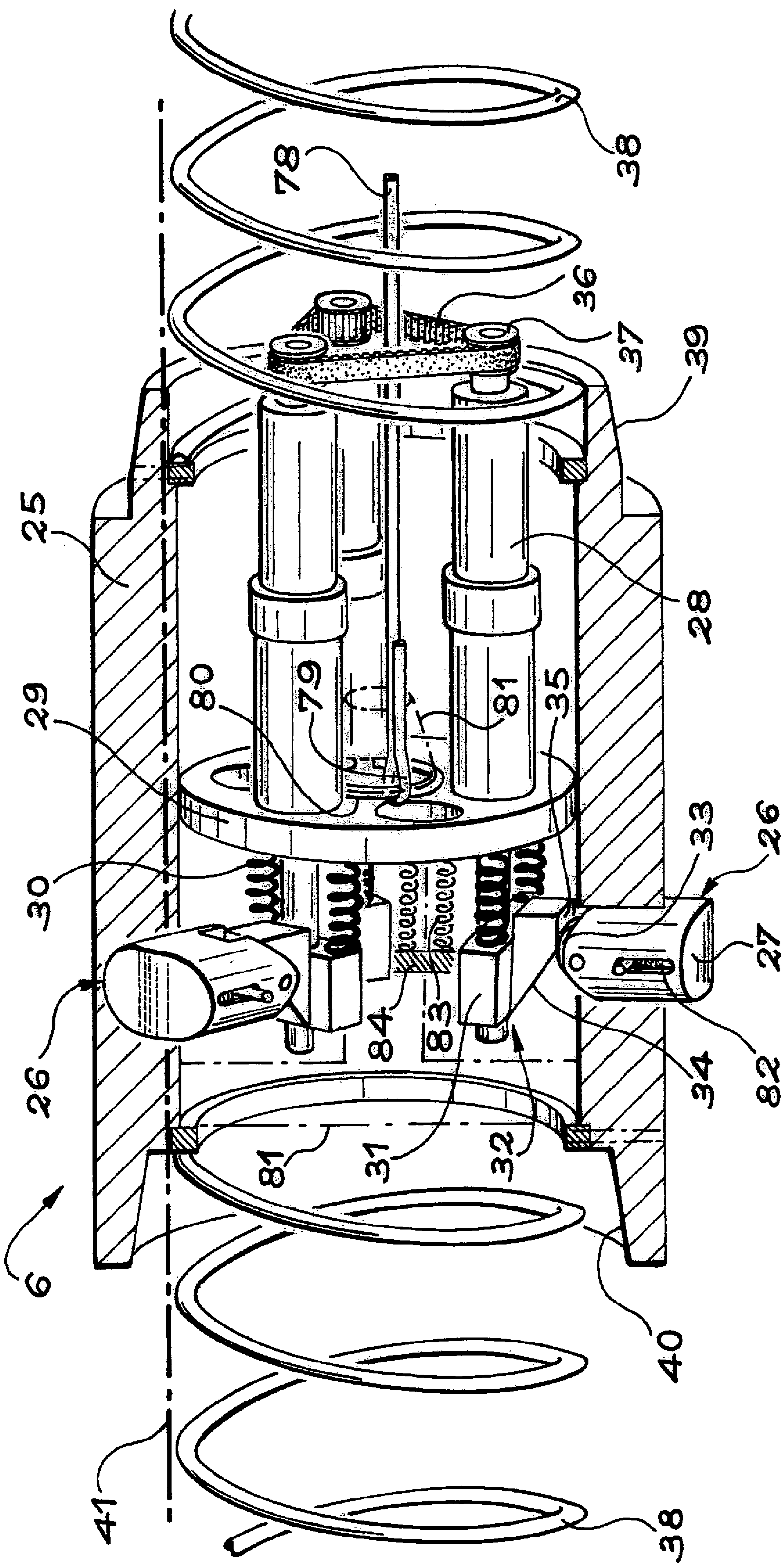

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FIG. 3

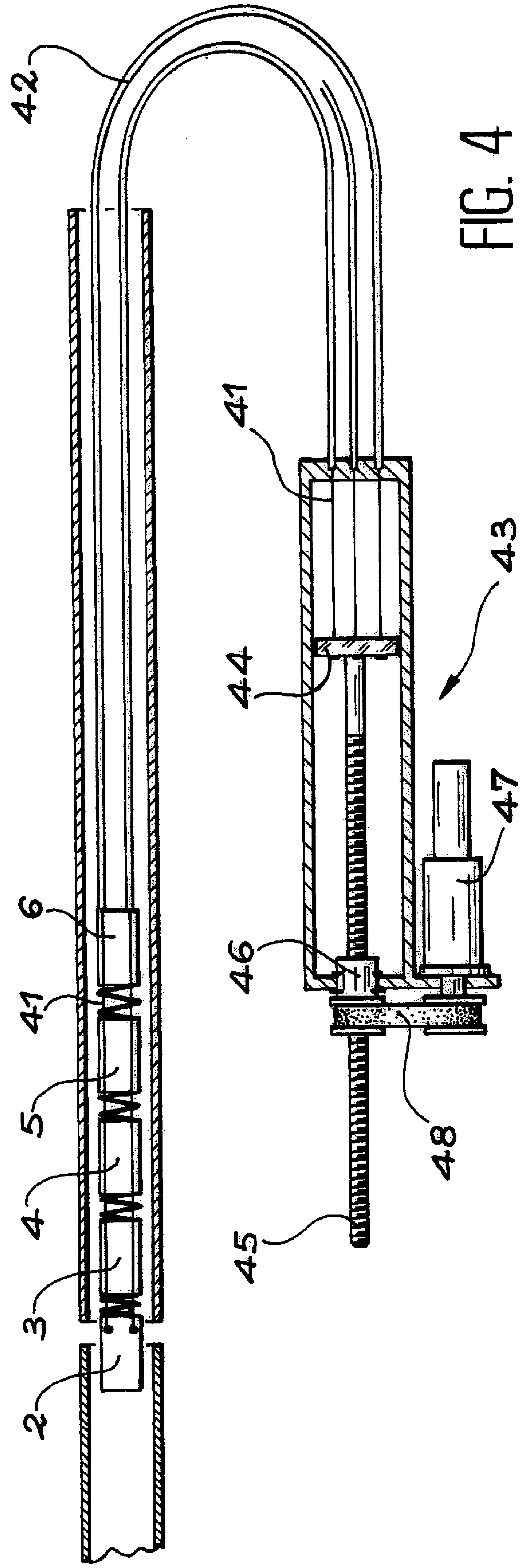


FIG. 4

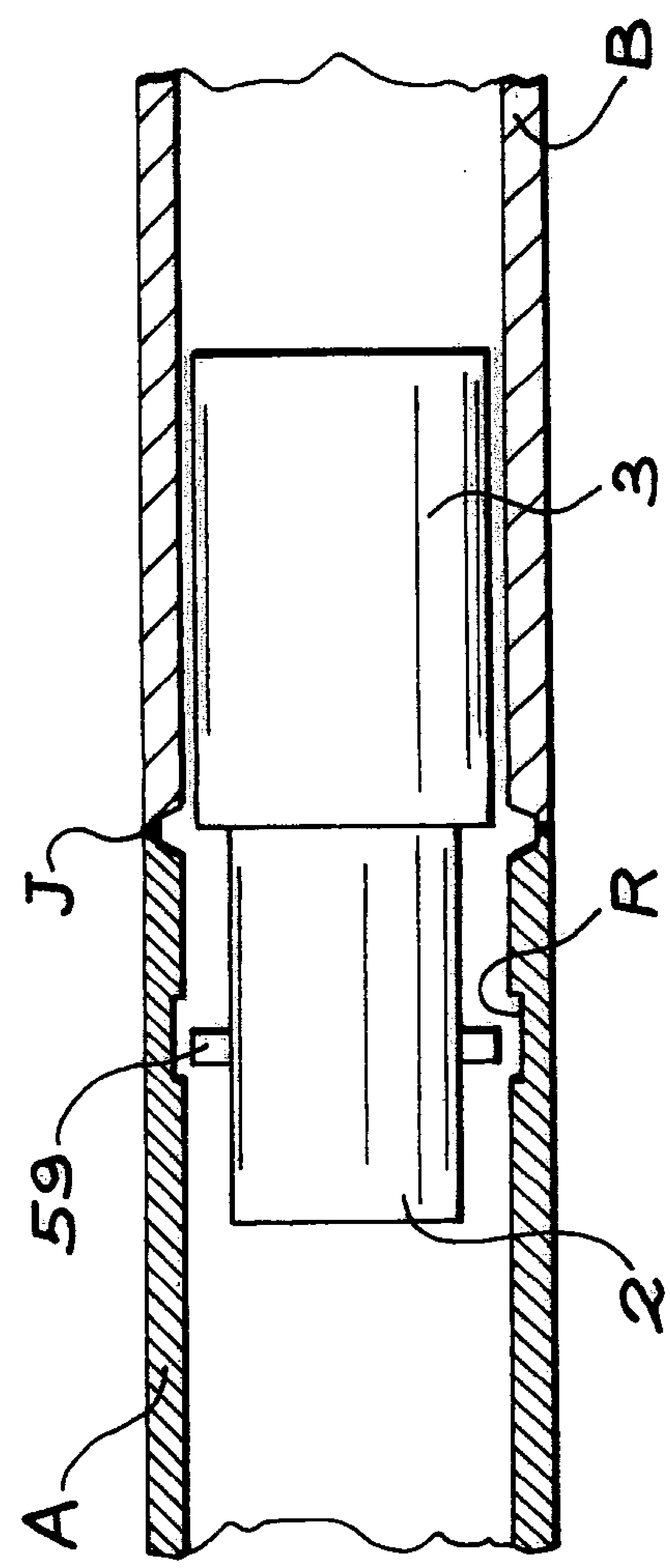


FIG. 6

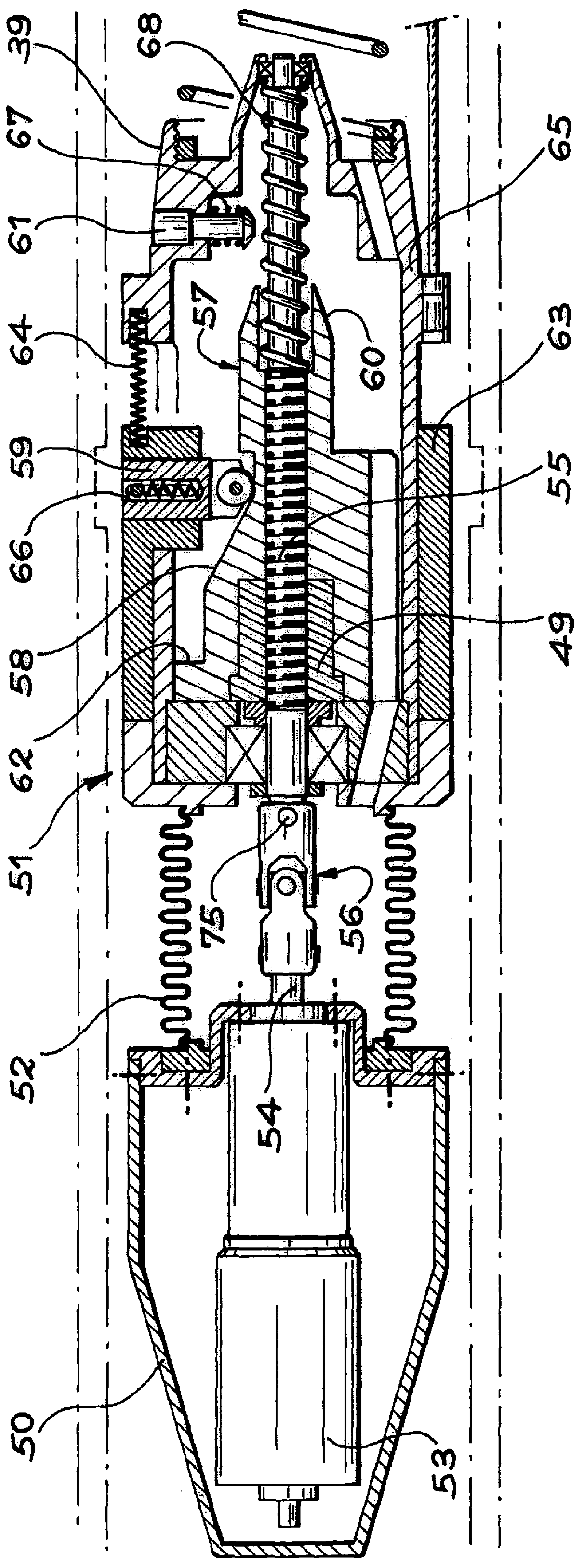


FIG. 5

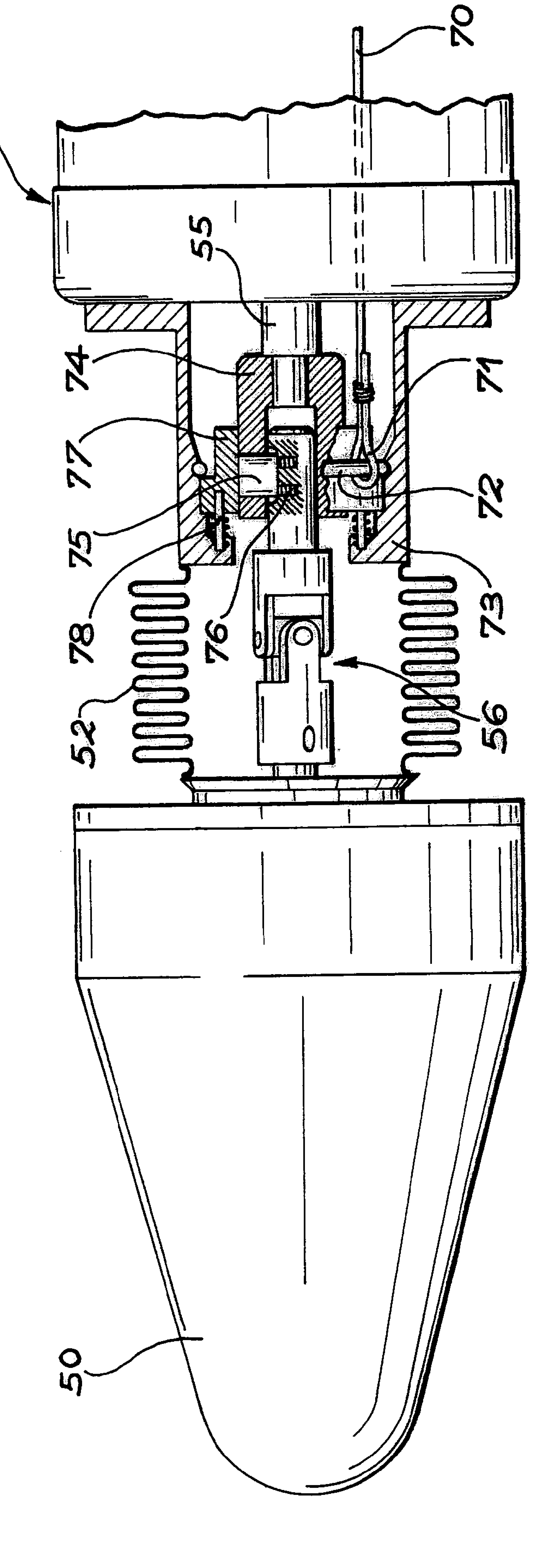


FIG. 7

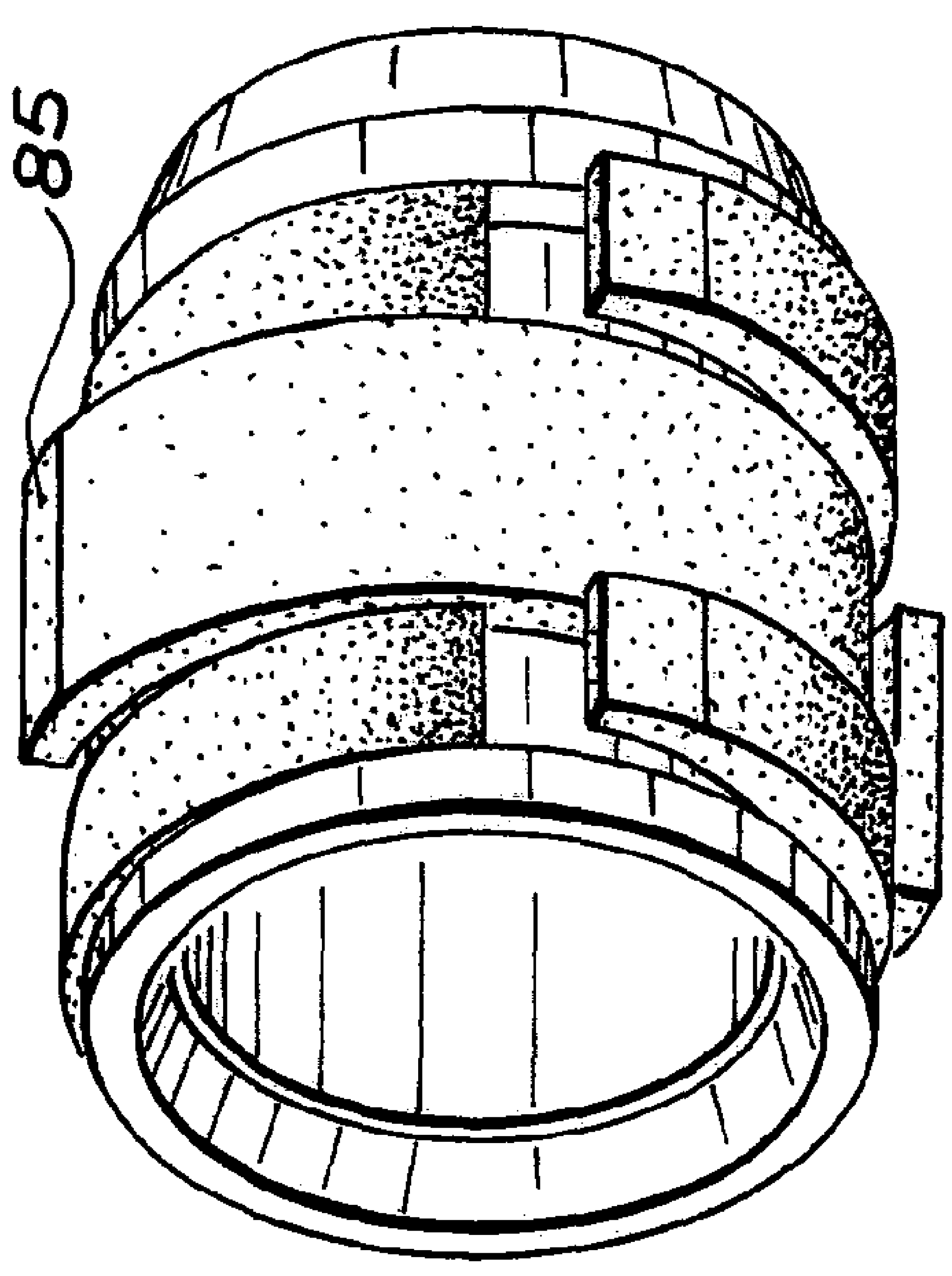


FIG. 8

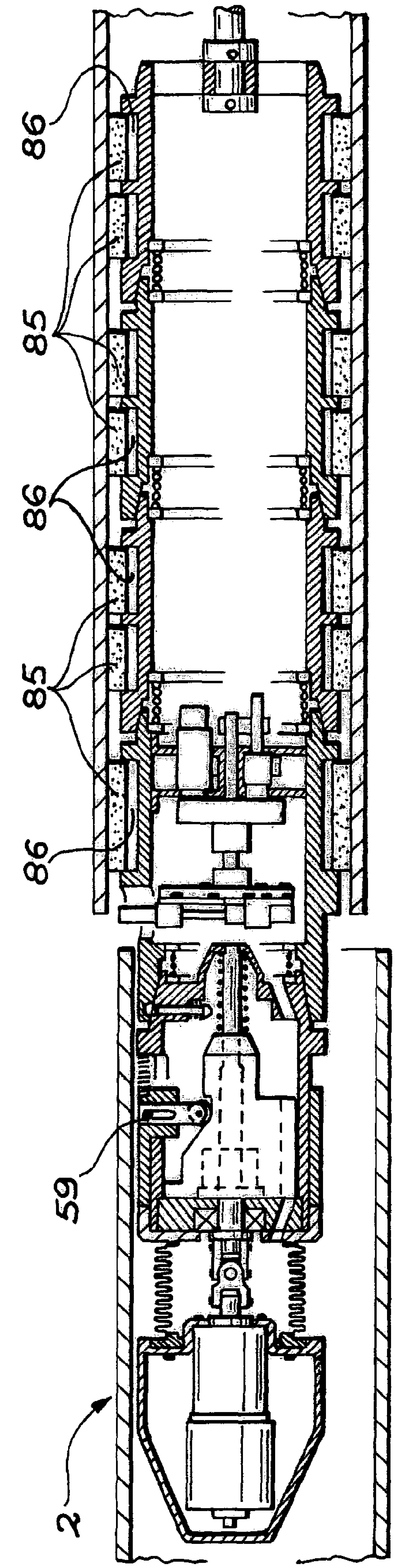


FIG. 9

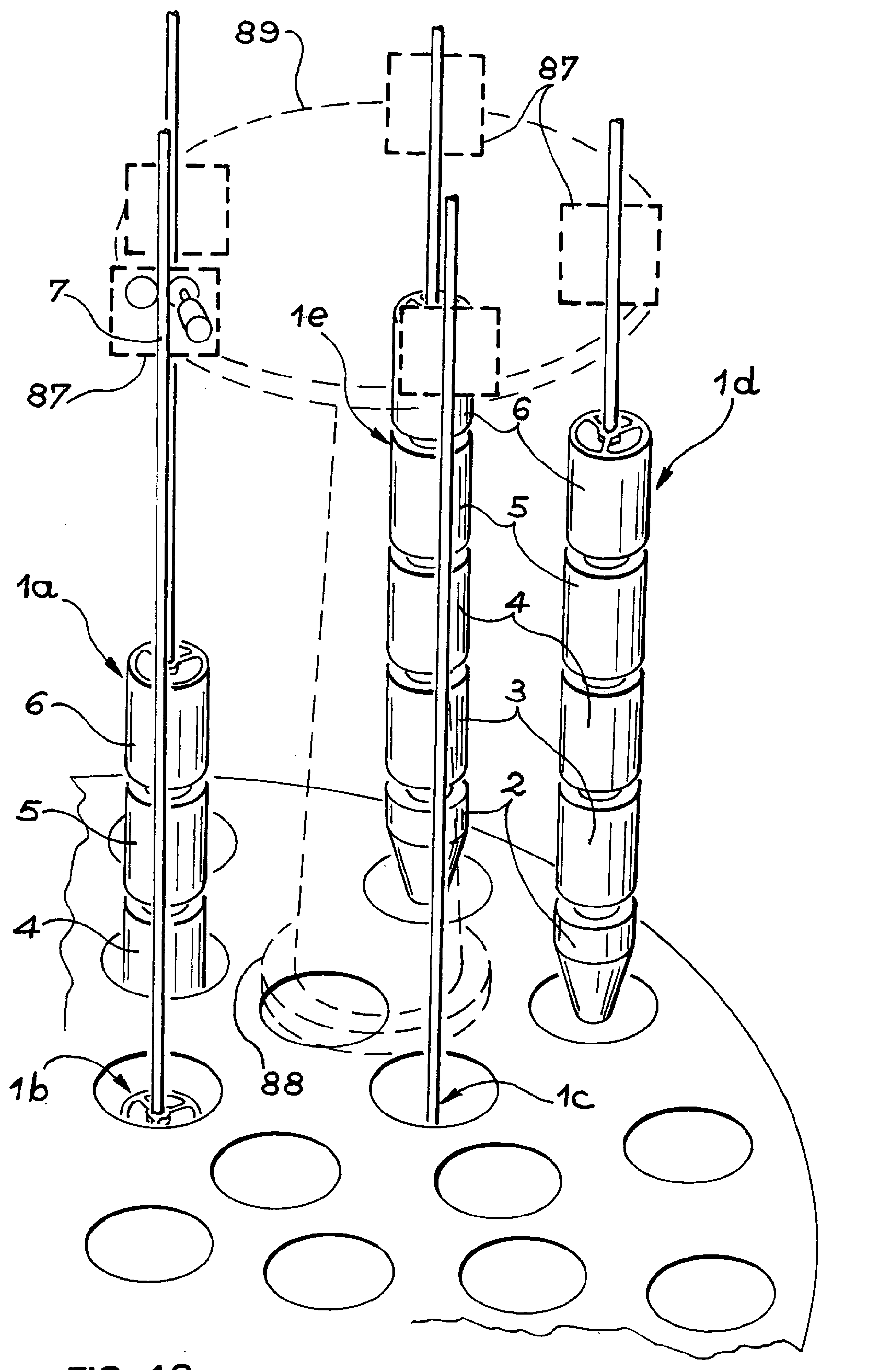


FIG. 10

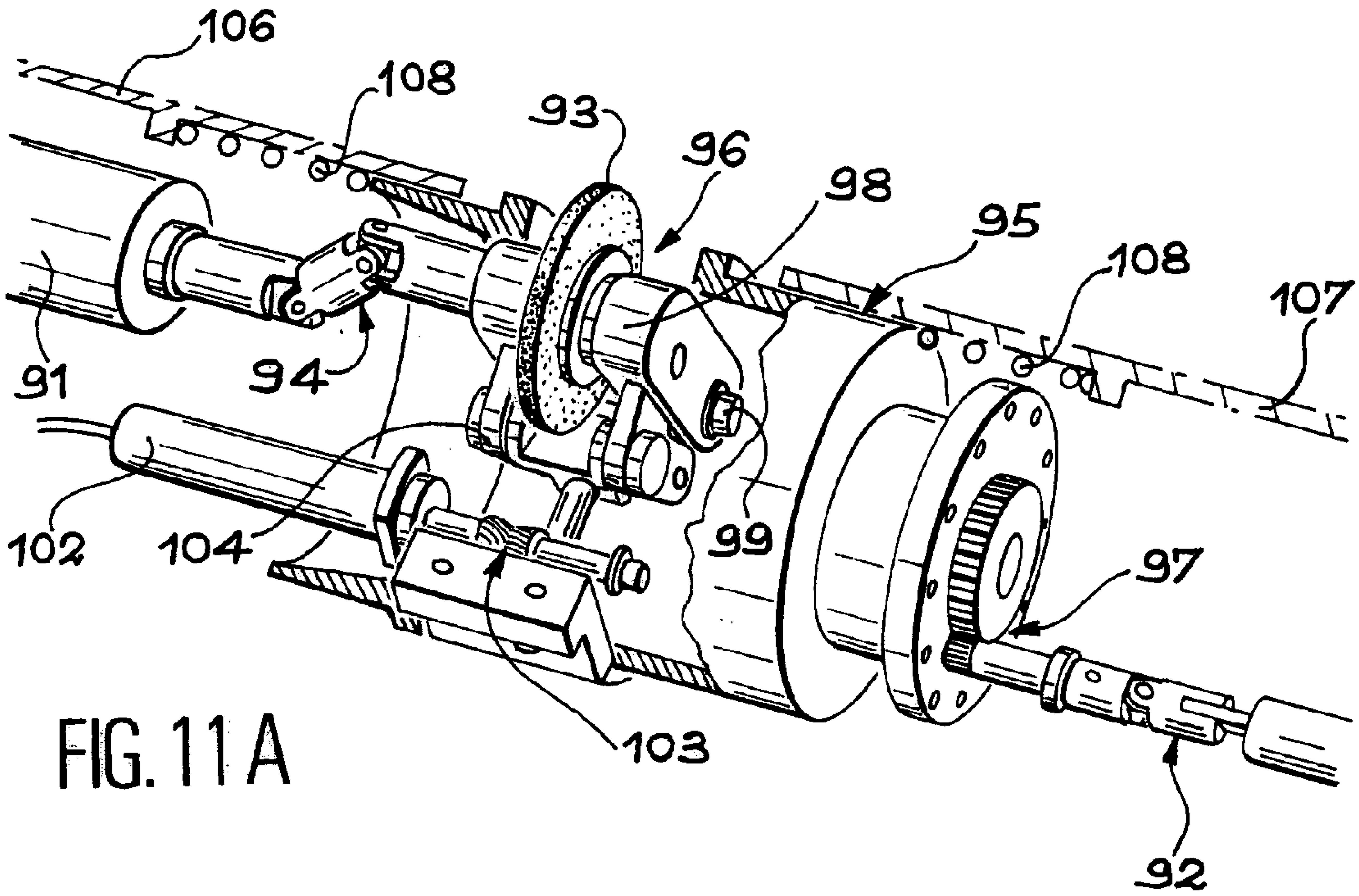
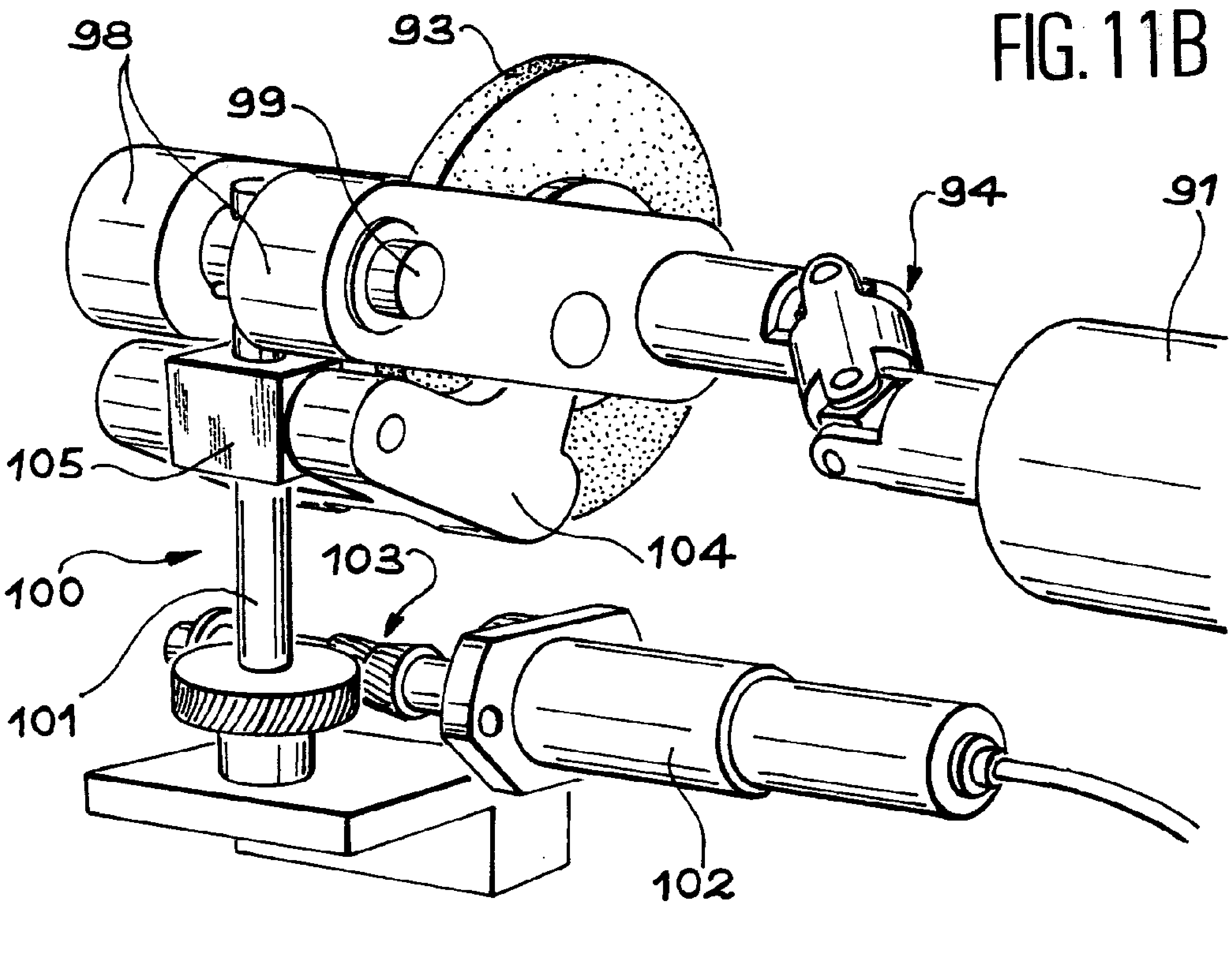


FIG. 11 A

FIG. 11B



ROBOT VEHICLE ADAPTED TO OPERATE IN PIPELINES AND OTHER NARROW PASSAGES

[**0001**] This application claims priority based on International Patent Application No. PCT/FR01/02324, entitled "Mobile Robot That Can Operate In Pipes Or Other Narrow Passages" by Yann Perrot, Olivier David and Jean Lehu, which claims priority of French application no. 00/09387, filed on Jul. 18, 2000, and which was not published in English."

DESCRIPTION

[**0002**] The domain of the invention is mobile robots for work, inspection or generally displacement inside pipework or other narrow passages.

[**0003**] Robots composed of a small vehicle or an inert module pushed from behind are known, for penetration into pipes and to carry out specific work or inspections in pipes. However, it may be difficult when these robots have to go round bends in the pipework, since they cannot be very long otherwise they would get jammed. One possible solution is to construct a robot consisting of a train of modules formed to be flexible, but it then becomes difficult to stop and hold the robot at a specific place in the pipework and even more difficult to fix it such that it remains immobile despite large forces that it may transmit to the pipework, and despite large reaction forces that may be applied to it during specific work such as machining of the inside of the pipework.

[**0004**] The invention offers a solution to this problem; it relates to a robot free to move by sliding in pipework or in another narrow passage, composed of a train of modules connected by flexible links and characterised in that it comprises means of fixing the modules together.

[**0005**] Thus, the robot is flexible so that it can go around bends in pipes, but becomes rigid when required and is then capable of being fixed firmly in the pipework and supplying good resistance. Above all, the inhibition of flexible links stiffens the train to resist bending.

[**0006**] Some favourable implementations of the invention make it possible to hold the robot at a chosen location in the pipework, by controlling appropriate mechanisms. It then becomes possible and beneficial to provide the robot with manual release mechanisms so that retraction of the holding mechanisms can be controlled manually so that the robot can be made free to move again even if direct control of the holding mechanism motors fail.

[**0007**] A particular operation consists of assembling segments of pipework put end to end in sequence; the robot according to the invention can do this operation if it is built such that two portions of an anterior module can be brought towards each other, one of these portions being held in place on the free segment and the other being fixed to the previously assembled length of the pipework.

[**0008**] Other important elements of the invention, and particularly specific means of performing the functions described above, will be described in detail with reference to the following figures:

[**0009**] **FIG. 1** is an overview of the robot,

[**0010**] **FIG. 2** is a view of a propulsion module,

[**0011**] **FIG. 3** is a view of a holding module,

[**0012**] **FIG. 4** shows the train stiffening system,

[**0013**] **FIG. 5** is a view of an anterior module,

[**0014**] **FIG. 6** illustrates the anterior module immobilised in the pipework,

[**0015**] **FIG. 7** illustrates the forced release mechanism of the anterior module,

[**0016**] **FIG. 8** shows another holding means for a module,

[**0017**] **FIG. 9** illustrates a train composed of such modules,

[**0018**] **FIG. 10** illustrates a case in which the invention is used,

[**0019**] **FIGS. 11A and 11B** show a module carrying a machining tool.

[**0020**] The embodiment of the invention as shown in **FIG. 1** in a pipe bend comprises five modules numbered from **2** to **6** from the head to the tail; the head or anterior module is an alignment module **2** that the robot **1** uses to form a path in the pipework; the next module is a tool module **3** carrying a working tool; the next module is a power module **4** supplying energy to the previous module; the fourth module is an auxiliary functions module **5**; the tail or posterior module in this embodiment is an immobilisation module **6**. Neither the number nor the function of the modules characterise the robot according to the invention or restricts its scope, since it is obvious that the invention could be implemented with different robots. In particular, a propulsion module that will be described a little later could be added at the tail. In this embodiment, it would be superfluous because robot **1** is designed to be pushed inside the pipework by means of a flexible rod **7** attached to the rear of the tail module through crimping **8**. The rod **7** is flexible at bends in the pipe, but it transmits all longitudinal forces imposed on it and therefore pushes the robot **1** forwards. It tends to deform at the largest possible angle of curvature in a bend, separating from the extrados as shown in the diagram in the right part of **FIG. 1**, at location **9**. Therefore, it is fairly easy to calculate the penetration of the robot **1** as a function of the length of the rod that has penetrated into the pipework.

[**0021**] **FIG. 2** shows a standalone propulsion module **10**. Its enclosure **11** contains a motor **12** on which the shaft **13** is a screw driving three toothed wheels **14**. Each of them drives a pulley **15** that is coaxial with it, and another pulley **17** fixed to a roller **18** through a belt **16**. The rollers **18** are distributed at 120° around a rear circumference of the enclosure **11** and are placed at the end of levers **19** hinged about an axis **20** at their opposite end and mutually separated by springs **21**, so as to withdraw rollers **18** away from the enclosure **11** until they are pressed into contact on the wall of the pipework. Another similar expandable roller system, globally referenced **22**, is placed in front of the propulsion module **10**, except that these rollers are not driving and therefore they simply complement centring of the module **10** in the pipework. A double universal joint **23** connects the module **10** to the back of the immobilisation module **6** so that a radial alignment fault can be accepted between them. Since the motor **12** is fairly long and thin, the enclosure **11** has a recessed shape at the centre so that it can pass through the tightest bends despite its length.

[**0022**] At least two modules have an immobilisation or holding system in the pipework that will be described below; one of them is the immobilisation module **6** fully illustrated in **FIG. 3**; its enclosure **25** is perforated by three concentric holes through which diverging pins **26** can pass, and finishing at the pipework on a bearing surface **27**. The enclosure **25** surrounds three motors **28** fixed to a common support plate **29** and that rotate the screws **30** designed to move the threaded cams **31** forwards, the surfaces **32** of which push on the back faces **33** of the pins **26**. The cam surfaces **32** are not simple wedge surfaces, but comprise at least two slopes, the first **34** being steeper so that the pins **26** can be pushed more quickly while the other surface **35** is shallower and adjusts the pressure force of the pins **26** on the pipework. The rotations of motors **28** are synchronised using a belt **36** tensioned in a triangular arrangement around three gears **37** at the ends of the screws **30** at the other end of the motors **28**. As a variant, it would be possible to have a single motor to control the three screws **30** at the same time, using separate transmission means.

[**0023**] We will now describe an essential aspect of the invention with reference to this **FIG. 3**, and **FIG. 4**; they are means of physical and electrical connections of modules **2** to **6** in the train that comprise helical springs **38** fixed between two consecutive modules, and an outside conical male face **39** on the enclosure of each module at the back and an internal female conical face **40** at the front. The only exception is the alignment module **2**, which is specially shaped at the front so that the robot **1** can easily form its path. The springs **38** are associated with stiffening cables **41** that pass through all modules **2** to **6** and extend as far as the alignment module **2**, behind which they are connected. In fact, there are three stiffening cables **41** distributed uniformly around the circumference for a balanced transmission of the force. The stiffening cables **41** slide in ducts **42** behind the immobilisation module **6**, extending as far as a tension mechanism **43** comprising a distribution plate **44** to which the stripped ends of the stiffening cables **41** are attached, a screw **45** at the end of which the distribution plate **44** is fixed, a nut **46** fitted on the screw **45** and a motor **47** making the nut **46** turn driven by a pulley and belt transmission **48**; the screw **45** slides pulling the distribution plate **44** with it so as to pull the alignment module **2** backwards. But if the immobilisation module **6** is held on the pipe by the expanded pins **26**, it will remain immobile, the other modules **2** to **5** will move closer to it and the train will contract, until the male conical surfaces **39** penetrate into the female conical surfaces **40** such that the consecutive modules **2** to **6** join together forming a single compact high strength robot element, particularly incapable of bending. When the stiffening cables **41** are released, the springs **38** can relax and the train then becomes flexible once again. In a variant not shown, a cable tensioning device is installed onboard.

[**0024**] We will now describe **FIG. 5** and the alignment module **2** of the robot **1** in the pipework. It comprises a conical head **50** at the front connected to a main body **51** through a bellows **52** and containing a motor **53**, the shaft **54** of which rotates a ball screw **55** housed in the main body **51** through a double universal joint **56** that surrounds the bellows **52**. A nut **49** driven by the ball screw **55** on the centre line of the ball screw drives a complex shaped cam **57** that occupies most of the main body **51**. It comprises main oblique tracks **58** to control the expansion of the clamping pins **59** similar to the pins (**26**) described for the immobilisation module **6**, secondary oblique tracks **60** to control the expansion of connection pins **61** to the next module **3**, and a shoulder **62** at the back to control the backwards displacement of an enclosure skin **63** carrying pins **59** along the main body **51**. This displacement is directed against springs **64** fixed to a main enclosure **65** of the main body **51** and that push the enclosure skin **63** forwards; as a reminder, note the other springs **66** and **67** that pull pins **59** and **61** towards the inside of the main body **51** and a spring **68** that pulls the cam **57** forwards. The advantage of this innovative assembly can easily be understood with reference to **FIG. 6**; the pins **59** expand and enter into a groove R around the edge of a forward portion A of the pipework. This groove R marks the progress of robot **1** in the pipework, indicating a stop position at which work can be done. However, the front portion A is not necessarily joined to the rear portion B of the pipework if the work to be done is to weld the joint J between them.

[**0025**] Therefore, the first effect of a displacement of the cam **57** is to immobilise the main body **5** of the alignment module **2** in the forward portion A of the pipework and on the tool module **3** by extending the pins **59** and **61**; the shoulder stop **62** on the enclosure skin **63** then pushes the enclosure skin, the pins **59** and finally the front portion A until it touches the rear portion B. The joint J is then formed in front of the tool module **3** that can begin to work. The robot **1** can thus be used to assemble a complete line of pipes from the inside. The bellows **52** and the ball joint **56** are sufficiently flexible so that the conical head **50** can be engaged in the badly positioned forward pipework A, that can then be straightened by the cam **57** mechanism.

[**0026**] In other applications, the pins **59** are only used to immobilise the train of modules **2** to **6** inside the pipework, and the module **3** tool may be a grinding wheel or a knife or a sensor to perform various types of inspections or machining on the joint J, or to cut it; the alignment module **2** then holds the forward portion of the pipework A on the other side of the cut; normally, there is no need to worry about a misalignment in the pipework due to internal stresses at the cut at joint J, since the stiffness of the assembly of the train of modules **3** and their fixity is not sufficient to prevent all deformation of the robot **1**.

[**0027**] Another aspect of the invention, also present on the alignment module **2**, will now be described with reference to **FIG. 7**. This aspect relates to the need to control loosening of pins **59** and **61** even if there is a failure in the control motor **53** of the cam **57**, or for any other reason. A manual command using a cable **70** parallel to the stiffening cables **41** is then provided, this cable projecting backwards from the pipework like the stiffening cables. The end of the cable **70** is wound in a loop **71** around a safety ring **72** that holds a mobile ring **77** in place close to a shoulder **73** at the end of the main body **51**, despite the action of springs **78** compressed between the shoulder **73** and the mobile ring **77**.

[**0028**] However, a fairly strong tension on the cable **70** is sufficient to tear the safety ring **72** out of the groove of the main body **51** that held it in place, which releases the mobile ring **77** that the springs **78** push backwards. It releases a pin **75** that fixes a fixed ring **74** attached to the ball screw in rotation to the output shaft from universal joint **56**; a spring **76** ejects the pin **75** and breaks the connection between the ball screw **55** of the motor **53**; the spring **68** can then expand and push the cam **57** forwards due to the reversibility of the transmission between the ball screw **55** and the nut **56**; and the springs **66** and **67** make the pins **59** and **61** retract.

[**0029**] A similar device is provided for the other tightening pins. Returning to **FIG. 3**, it can be seen that there is one for the immobilisation module **6**; a cable **78** similar to cable **70** terminates in a loop **79** around a safety ring **80** so that the safety ring is torn off when it is pulled, which releases the support plate **29** carrying the motors **28** from a nose **81** fixed to the enclosure **25** of the module. Springs **83**, previously compressed between the carrier plate **29** and the distribution plates **84** fixed to the enclosure **25**, then expand to push the support plate **29** backwards so as to make the cams **31** withdraw. The relaxation of springs **82** placed between the enclosure **25** and the pins **26** retracts the pins and releases the robot.

[**0030**] **FIGS. 8 and 9** show that other immobilisation means for the modules could be used, and particularly shape memory pads **85** that can be in the form of discontinuous hoops around the different modules. A shape memory alloy part has the special feature that it can take on two different shapes by changing its metallurgical structure at a transition temperature, and return to the shape that was imposed on it when its temperature increases to above the transition temperature in a preliminary manufacturing step. In this case, the pads **85** tend to straighten above the transition temperature, and their ends are trapped in contact with the inside face of the pipework. At the same time, their ends remain in the grooves **86** in the modules, which holds them firmly in place. Electrical power supplies, not shown, increase the temperature of the pads **85**. This system has the advantage that cutting off the electrical current necessarily brings the pads **85** back to their initial shape and releases the module train, and the release cable systems described with reference to **FIG. 7** become unnecessary. However, **FIG. 9** suggests that it is useful to hold the immobilisation pins **59** of the alignment module **2** that are also useful as positioning references in the groove R of the pipework for all tasks in which the robot has to be stopped at a specific location.

[**0031**] Obviously, all types of tools can be used; the robot was developed specifically to be capable of performing processes that involve five operations on the pipework, namely cutting, knurling, spot welding, welding and ultrasound inspection. Five similar module trains can advantageously be used, in which the tool module **3** is different in each train. As can be seen in **FIG. 10**, the trains **1***a* to **1***e* may be suspended in a circle from a drum **86** by independent advance mechanisms **87** lowered in sequence into the line of pipework to be treated after rotation of the drum **86** that rotates on a base **88**. For example, it would be possible to treat several lines in nuclear power station steam generators that comprise a large number of parallel pipework lines to be treated, with a phase offset for each line, and pushing several module trains into different lines simultaneously.

[**0032**] **FIGS. 11A and 11B** show that the tool modules **3** usually include two motors **91** and **92** on each side of a tool **93** (in this case a cutter that could be replaced by a circular grinding wheel); the first of these motors rotates the tool **93** around its axis through a universal joint **94**, and the second makes a cylindrical casing **95** rotate outside a slit **96** from which the tool **93** projects, about its axis by a gear **97**. The tool **93** is at the end of a lever **98** that pivots about an eccentric axis **99** in the casing **95** and that is pushed by a linkage mechanism **100** with screw control **101** activated by a third motor **102** and a connecting gear **103**, and a rocker arm **104**, the opposite ends of which are articulated to the lever **98** and to a gland **105** engaged in the screw **101**; furthermore, the screw **101** reaches the shaft **99**. Therefore, movements of the motor change the distance between the gland **105** and the shaft **99** and the angle of the lever **98** and the rocker arm **104**, which makes the rocker arm rotate and extend and retract tool **93** before and after its work on a pipework joint.

[**0033**] Circular joints can be machined by a combination of the rotation movement of the tool **93**, the exit movement of the tool **93** and the rotation movement of the casing **95**. We will not discuss these machines for machining inside a pipework any further, some of which have already been designed, but we will simply mention once again that the casing **95** extends between two half-enclosures **106** and **107** of the tool module **3**, which come closer to each other when the springs **38** are compressed until they come into contact with the casing **95** while allowing the casing to rotate. Complementary springs **108** separate the two half-enclosures **106** and **107** when the springs **38** are released.

1. Robot free to slide inside pipework or another narrow passage, composed of a train of modules (**2** to **6**, **10**) connected by flexible links (**38**), characterised in that it comprises means of fixing (**41**) modules to each other to stiffen the train.

2. Mobile robot according to claim 1, characterised in that at least some of the modules comprise means (**26**, **59**, **85**) of achieving fixity in the passage.

3. Mobile robot according to claim 2, characterised in that the immobilisation means consist of the pins activated by sloping cam surfaces (**57**) sliding axially in the modules.

4. Mobile robot according to claim 3, characterised in that the cam surfaces have two different slopes including a first steeper slope (**34**) acting firstly on the pins, and a second shallower slope (**35**).

5. Mobile robot according to claim 2, characterised in that it comprises positioning means (**59**) in a groove in the passage.

6. Mobile robot according to claim 5, characterised in that one of the modules is provided with means (**59**, **62**, **63**, **66**) of fixing two consecutive portions of pipework.

7. Mobile robot according to claim 6, characterised in that the positioning means and the fixing means comprise one of the immobilisation means (**59**) fitted on an axially mobile portion (**63**) of the module, and in that the fixing means also comprise a cam surface (**62**) pushing the axially mobile portion.

8. Mobile robot according to claim 2, characterised in that the immobilisation means comprise shape memory pads (**85**).

9. Mobile robot according to claim 1, characterised in that the module fixing means comprise at least one pulling cable (**41**), attached to one of the head modules (**2**), and opposing propulsion means (**7**, **10**) located on one of the tail modules (**6**, **10**).

10. Mobile robot according to claim 1, characterised in that the modules are connected together by springs (**38**) compressed by the fixing means (**41**).

11. Mobile robot according to claim 1, characterised in that the modules are provided with complementary conical engagement surfaces (**39**, **40**).

12. Mobile robot according to claim 2, characterised in that it comprises manual safety mechanisms to release the immobilisation means, comprising an activation cable and return springs acting on the immobilisation means.

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