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(54) **SURGICAL ROBOT SYSTEM FOR USE IN AN MRI**

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A61B 5/00	(2006.01)

(52) **U.S. Cl.**
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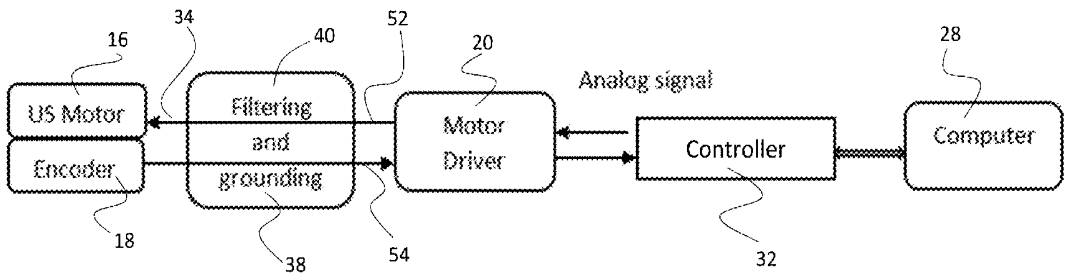
(57) **ABSTRACT**

A surgical robot assembly for use with an MRI includes a surgical robot, a controller, cables, a dedicated room ground and a filter. The surgical robot includes at least one ultrasonic motor and all the motors therein are ultrasonic motors. The controller is spaced from the surgical robot and is positioned outside the MRI room. The controller has at least one analog output; at least one digital input, at least two digital output, and at least one encoder reader channel. The cables are operably attaching the motors of the surgical robot to the controller and are RF shielded. The cables are operably connected to the dedicated room ground. The filter is operably connected to the cables which are operably connected between the motors of the surgical robot and the controller and the filter has a cut off frequency tuned to the MRI.



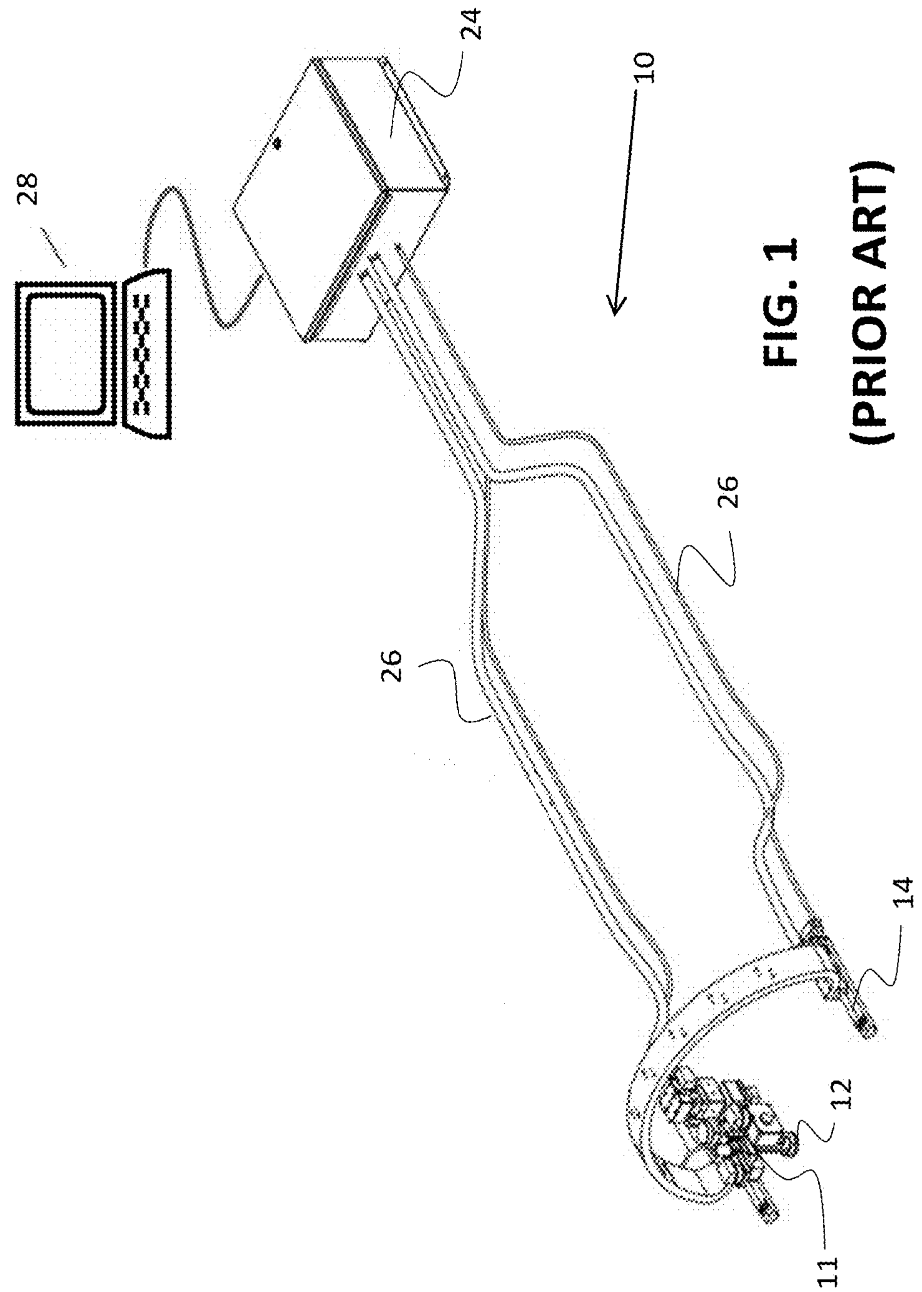


FIG. 1
(PRIOR ART)

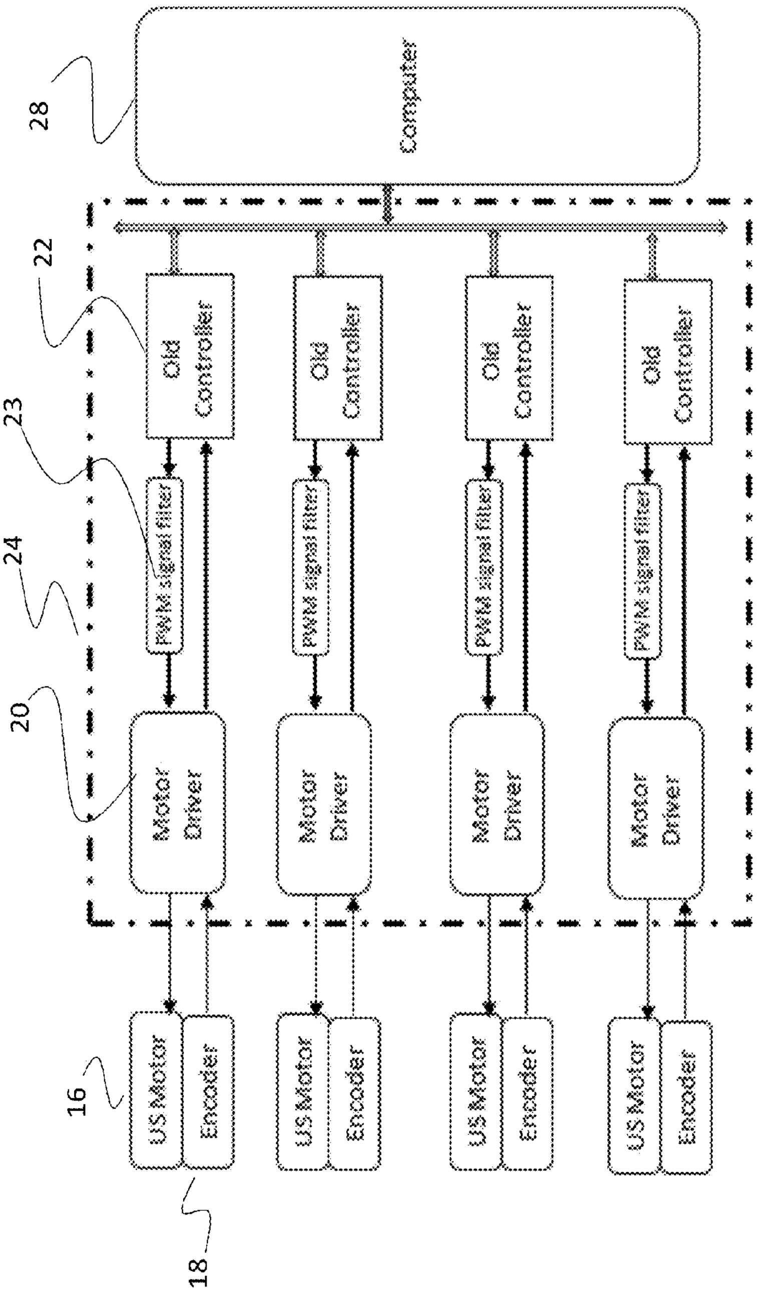


FIG. 2
(PRIOR ART)

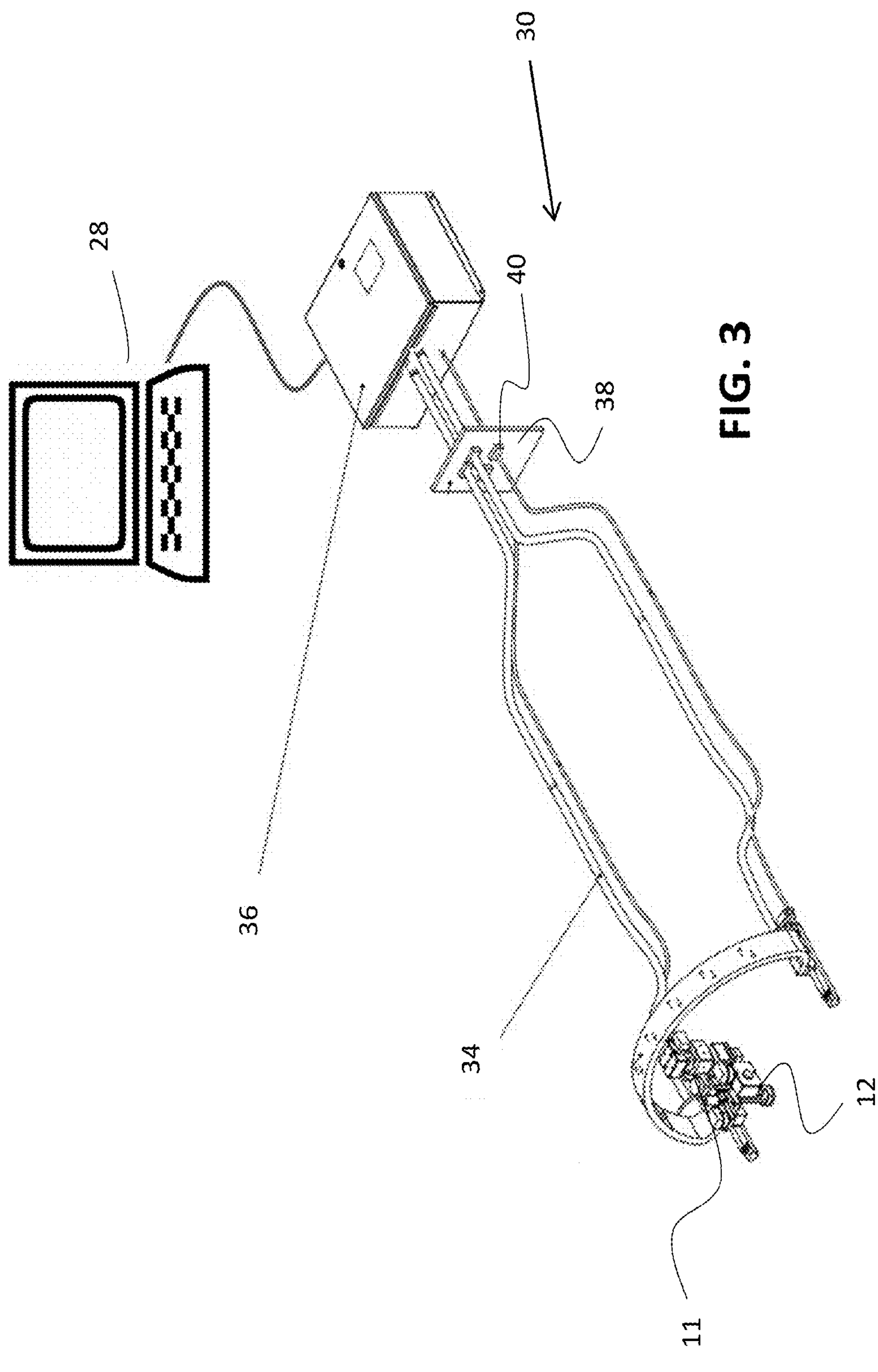


FIG. 3

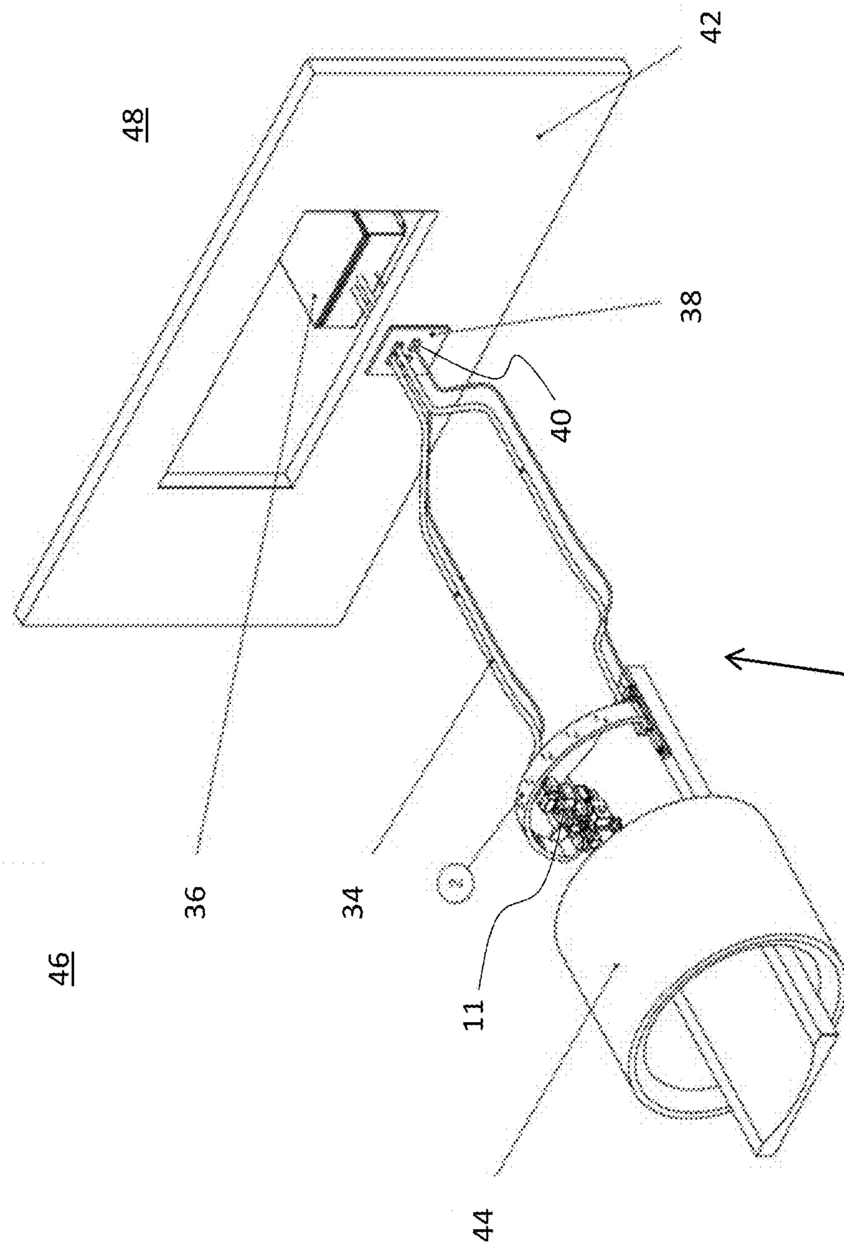
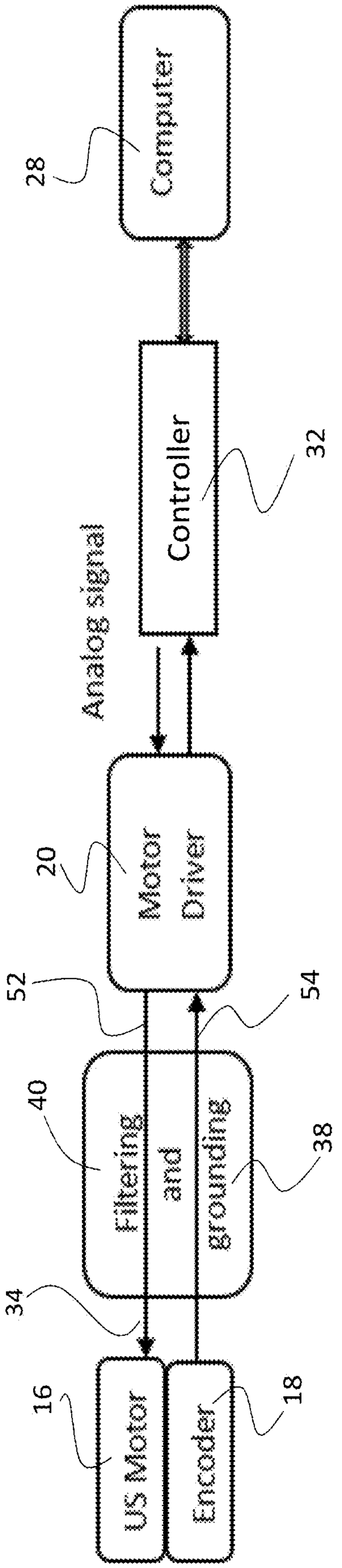
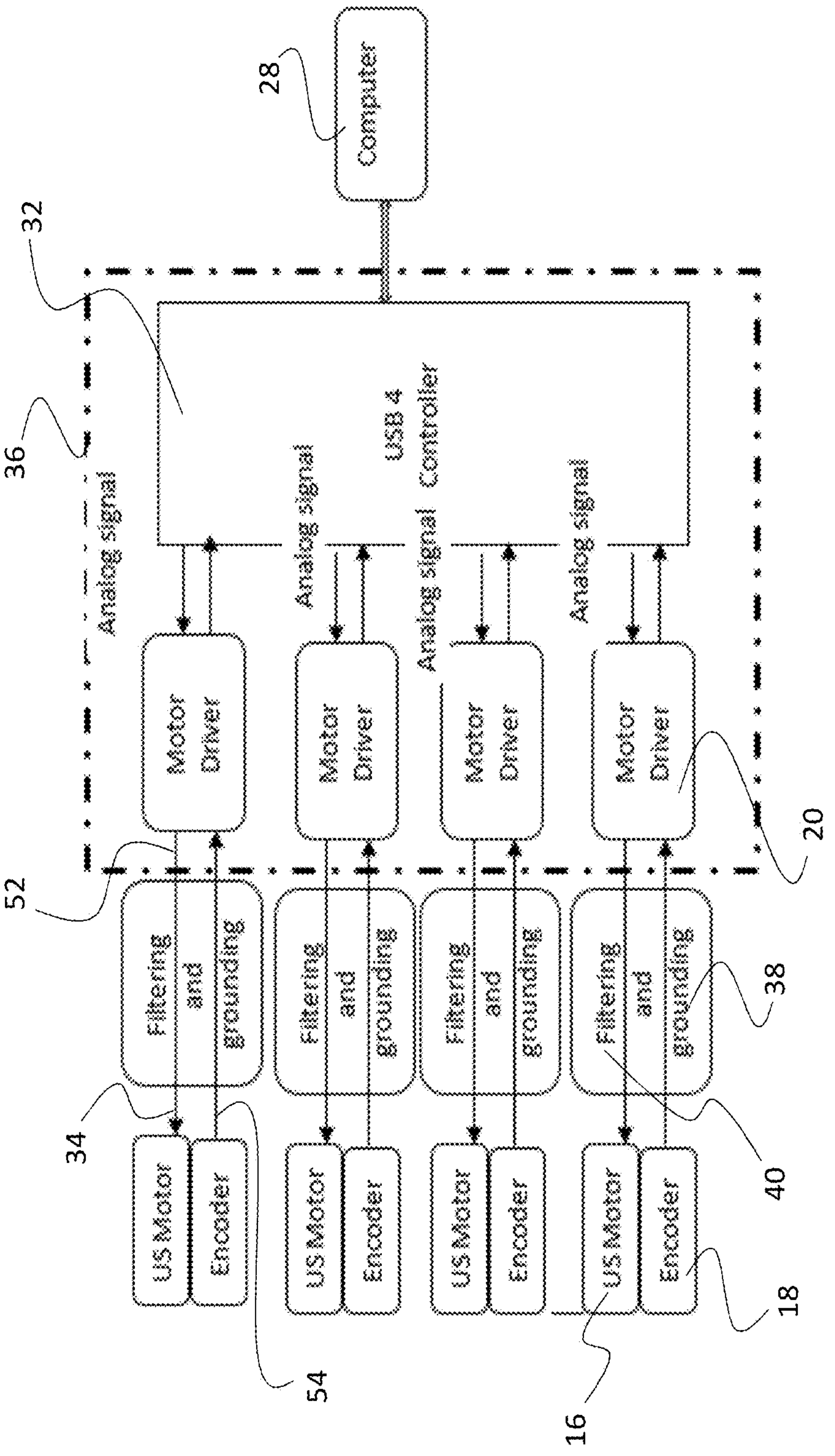


FIG. 4



Computer
28
Controller
32
Analog signal
Motor Driver
20
52
54
Filtering and grounding
40
38
34
US Motor
16
Encoder
18

FIG. 5



Computer
28
32
36
USB 4 Controller
Analog signal
Analog signal
Analog signal
Analog signal
Motor Driver
Motor Driver
Motor Driver
Motor Driver
20
52
Filtering and grounding
Filtering and grounding
Filtering and grounding
Filtering and grounding
38
40
34
US Motor
Encoder
US Motor
Encoder
US Motor
Encoder
US Motor
Encoder
54
16
18

FIG. 6

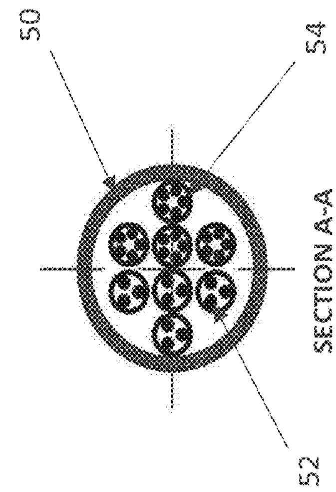


FIG. 7B

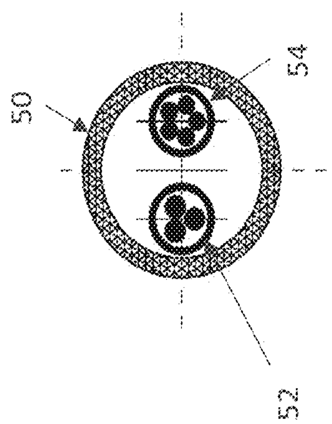


FIG. 7A

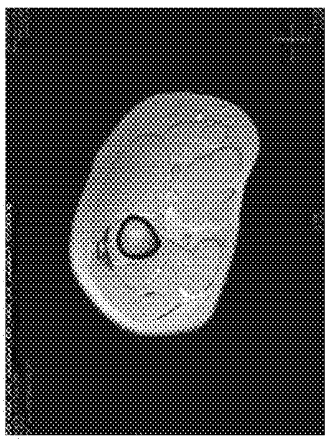


FIG. 8A

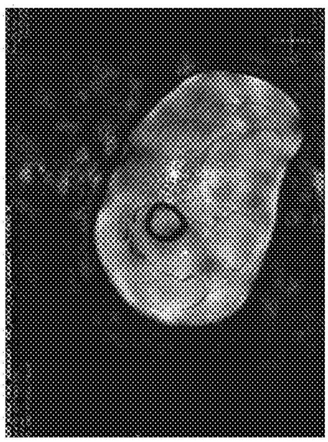


FIG. 8B

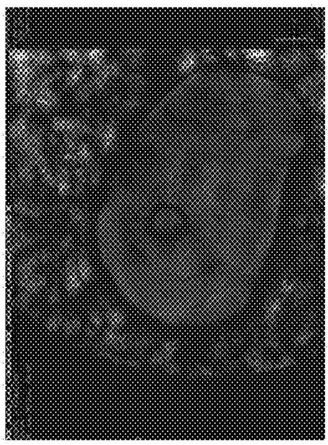


FIG. 8C

(PRIOR ART)

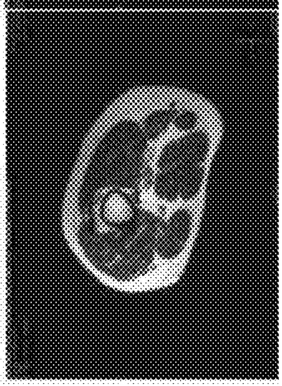


FIG. 9A

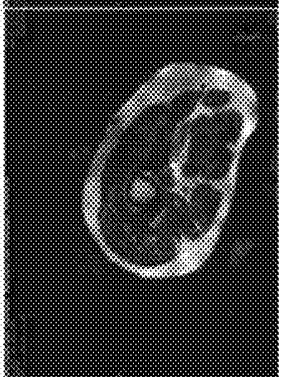


FIG. 9B

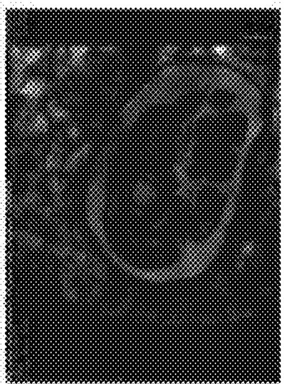


FIG. 9C

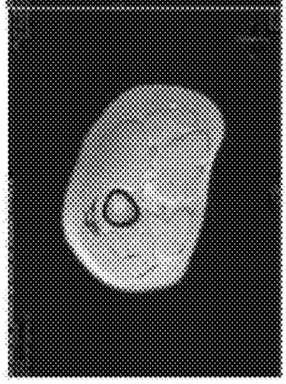


FIG. 10A

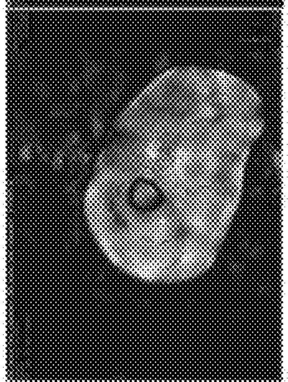


FIG. 10B

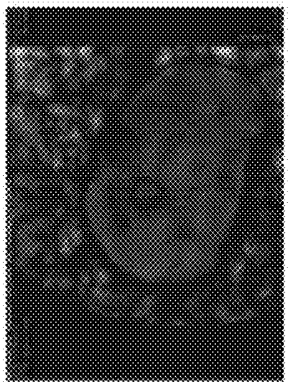


FIG. 10C

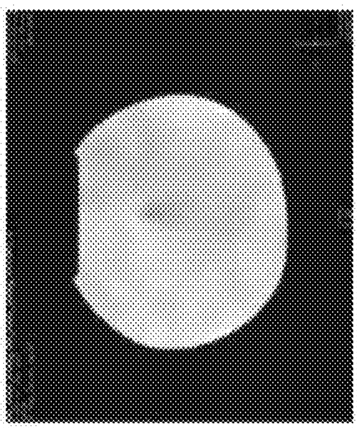


FIG. 11A

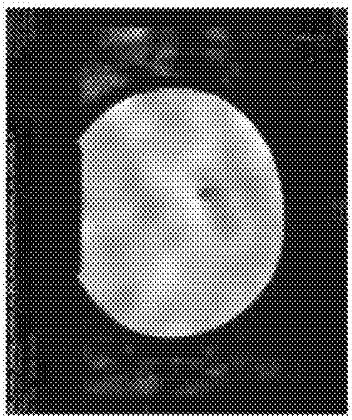


FIG. 11B

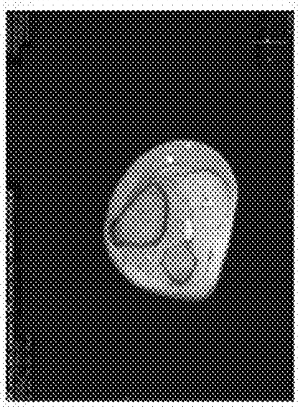


FIG. 12A

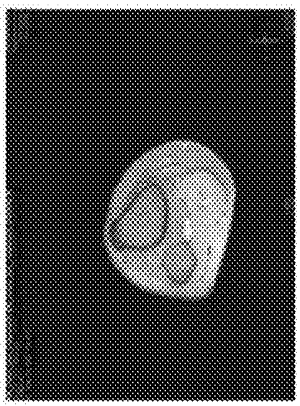


FIG. 12B

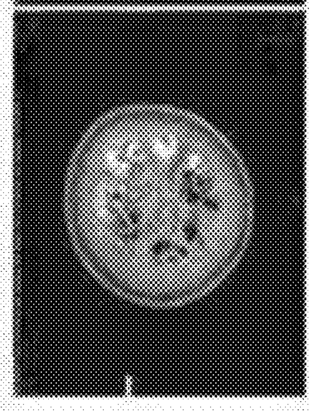


FIG. 13A

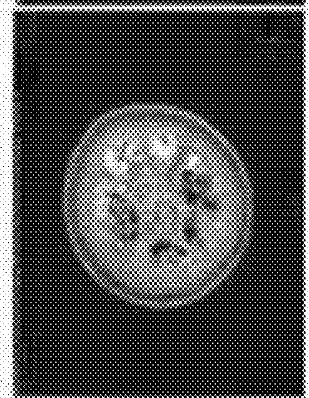


FIG. 13B

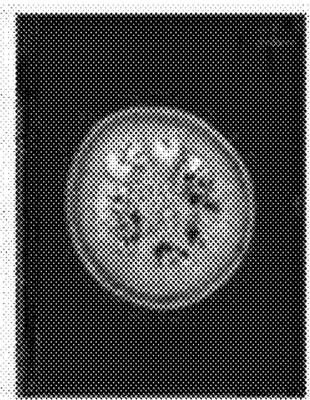


FIG. 13C

SURGICAL ROBOT SYSTEM FOR USE IN AN MRI

FIELD OF THE DISCLOSURE

[0001] This disclosure relates to medical robot systems and in particular a medical robot system for use in an MRI.

BACKGROUND

[0002] It is well known that medical resonance imaging (MRI) devices have excellent soft tissue resolution and generate minimal radiation hazard. Because of these advantages MRI-guided robotic-based minimally invasive surgery has become an important surgical tool.

[0003] There is a number of surgical robots currently in use but not all are compatible with an MRI. For example the Intuitive Surgical robot called the da Vinci™ is not compatible with an MRI. In contrast the Innomotion™ robot arm (Innomedic), the NeuroArm™ robot (University of Calgary), and the MRI-P™ robot (Engineering Services Inc.) are all MRI-compatible. However, even those robots which are MR compatible may not be able to be operated during MRI operation of scanning.

[0004] The main reasons that the robots have not been widely used in the MRI environment are MRI incompatibility and more particularly limitations of the real-time intra-operative imaging.

SUMMARY

[0005] A surgical robot assembly for use with an MRI includes a surgical robot, a controller, cables, a dedicated room ground and a filter. The surgical robot includes at least one ultrasonic motor and all the motors therein are ultrasonic motors. The controller is spaced from the surgical robot and is positioned outside the MRI room. The controller has at least one analog output; at least one digital input, at least two digital output, at least one encoder reader channel. The cables are operably attaching the motors of the surgical robot to the controller and are RF shielded. The cables are operably connected to the dedicated room ground. The filter is operably connected to the cables which are operably connected between the motors of the surgical robot and the controller and the filter has a cut off frequency tuned to the MRI.

[0006] The surgical robot may include a plurality of motors and the controller may include a plurality of analog outputs and the plurality of motors may be operably attached to the same controller.

[0007] The controller may be a USB4 controller.

[0008] The cables may be shielded with copper tube sleeves.

[0009] The surgical robot may include a plurality of motors and each motor has a cable between the motor and the controller and a plurality of cables may be bundled together in a copper tube sleeve. The plurality of motors may be operably attached to the same controller.

[0010] The dedicated ground may be attached to the cables and attached to a wall of the MRI room.

[0011] The filter may be a low pass filter.

[0012] The MR scanner may be a Philips 3.0T MR scanner and the low pass filter may have 3 DB cut off frequency at 3.2 MHz.

[0013] The filter may be a SPECTRUM CONTROL-56-705-003-FILTERED D Sub-connector.

[0014] Further features will be described or will become apparent in the course of the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] The embodiments will now be described by way of example only, with reference to the accompanying drawings, in which:

[0016] FIG. **1** is a perspective view of a prior art surgical robot for use in an MRI;

[0017] FIG. **2** is a schematic diagram of the connection between the ultrasonic motors and the computer in the prior art surgical robot of FIG. **1**;

[0018] FIG. **3** is a perspective view of an improved surgical robot for use in an MRI;

[0019] FIG. **4** is perspective view of the improved surgical robot similar to that shown in FIG. **3** but showing the MRI, an MRI table and an MRI room wall;

[0020] FIG. **5** is a schematic diagram of the connection between the ultrasonic motors and the computer of the improved surgical robot;

[0021] FIG. **6** is a schematic diagram of the connection between a plurality of ultrasonic motors and the computer of the improved surgical robot;

[0022] FIGS. **7**A and **7**B are cross sectional views of the shielding sleeve and cables of the improved surgical robot of FIG. **3**, wherein FIG. **7**A shows a single motor cable and a single encoder cable in a shielding sleeve and FIG. **7**B shows a plurality of motor cables and a plurality of encoder cables in a single shielding sleeve;

[0023] FIGS. **8**A, **8**B, and **8**C is a sequence of MRI images of apiece of meat of a 2-D FGRE (axial) taken using the prior art surgical robot, wherein FIG. **8**A is without the motor, FIG. **8**B is with the motor powered on without motion and FIG. **8**C is with the motor moving;

[0024] FIGS. **9**A, **9**B, and **9**C is a sequence of MRI images of a piece of meat of a 2-D FSE T2 (axial) taken using the surgical robot with shielded cables, wherein. FIG. **9**A is without the motor, FIG. **9**B is with the motor powered on without motion and FIG. **9**C is with the motor moving;

[0025] FIGS. **10**A, **10**B, and **10**C is a sequence of MRI images of a piece of meat of a 2-D FGRE (axial) taken using the surgical robot with shielded cables, wherein FIG. **10**A is without the motor, FIG. **10**B is with the motor powered on without motion and FIG. **10**C is with the motor moving;

[0026] FIGS. **11**A and **11**B is a sequence of MRI images of a phantom of a 2-D FSE T2 (axial) taken using the surgical robot with a USB4 controller and shielded cables, wherein FIG. **11**A is without the motor and FIG. **11**B is with the motor moving;

[0027] FIGS. **12**A and **12**B is a sequence of MRI images of a piece of meat of a 2-D FGRE (axial) taken using the improved surgical robot assembly of FIG. **3**, wherein FIG. **12**A is with the motor powered on without motion and FIG. **12**B is with the motor moving; and

[0028] FIGS. **13**A, **13**B and **13**C is a sequence of MRI images of a small watermelon of a 2-D FGRE (axial) taken using the improved surgical robot assembly of FIG. **3**, wherein FIG. **13**A is with the motor powered on without motion, FIG. **13**B is with the turret module of the surgical robot moving and FIG. **13**C is with surgical tool moving.

DETAILED DESCRIPTION

[0029] Referring to FIG. **1**, a prior art surgical robot system for use in an MRI is shown generally at **10**. By way of example, surgical robot system **10** includes a six-degree of freedom surgical robot **11** that uses ultrasonic motors. The surgical robot **11** has a surgical tool **12** attached thereto and is moveable on a pair of rails **14**. The surgical tool **12** may include an ultrasonic motor. The rails **14** typically will include a pair of ultrasonic motors for moving the surgical robot **10** along the rails.

[0030] Referring to FIG. **2**, the prior art surgical robot system **10** shown in FIG. **1** includes a plurality of ultrasonic motors **16**. Each ultrasonic motor **16** is operably connected to an encoder **18**. Each ultrasonic motor **16** and encoder **18** is operably connected to a motor driver **20**. The motor driver **20** is operably connected to a controller **22** which includes a PWM (pulse width modulation) and a PWM signal filter **23**. The controllers **22** and the motor drivers **20** are located in an electronics box **24** and are connected to the motors **16** and encoders **18** of the surgical robot **10** with cables **26**. The electronic cables **26** are shielded with an aluminium membrane. The controllers **22** in the electronic box **24** are operably connected to a computer **26**. The prior art robot assembly shown in FIGS. **1** and **2** is described in detail in U.S. patent application Ser. No. 14/619,978, filed Feb. 11, 2015 entitled "Surgical Robot" with Goldenberg et al. as inventors.

[0031] Prior art surgical robot system **10** is compatible with an MRI but if the motors are powered on the MR image is degraded in the form of noise and artifacts, the degradation of the MR image is increased if the motors are moving. This can clearly be seen in the MR images shown in FIG. **8** wherein FIG. **8**A is an MR image without motor, FIG. **8**B is with the motor powered on without motion and FIG. **8**C is with the motor moving.

[0032] The Ultrasonic Motors (USM) motion is generated mechanically by contact friction not electro-mechanically; there are no ferromagnetic parts. Thus, ultrasonic motors are considered suitable for the MRI environment, and may be used in devices working in or in the vicinity of MRI bore. However, the motor driver electronics that controls the motor motion generally produce noise on the MR images. Typically when the motor driver electronics are powered on they generates RF noise. In addition the motor/encoder cables may act as antennas emitting RF signals that interfere with the MR imaging process. This interference is in the form of noise and artifacts on the MR images. The noise and artifact constrain the use of ultrasonic motors in the MRI environment. In the prior art robot **10** shown in FIG. **1** the ultrasonic motors operation (motion) and MR imaging (scanning) are intercalate. Although widely accepted this solution limits operational functionality. Alternatively the ultrasonic motor drivers are "tuned-up" to the driver in the MRI firing sequence. The tune-up activates the driver when the scanning sequence is at rest, and vice-versa. This method is cumbersome to implement.

[0033] The improved surgical robot system for use with an MRI is described below with reference to FIGS. **3** to **6**. The improved surgical robot system **30** greatly decreases the noise and artifacts on the MRI image when the ultrasonic motors are in use. Referring to FIG. **3**, an improved surgical robot system is shown generally at **30**. The improved surgical robot system **30** is similar to that shown in FIG. **1**. However the connection of each of the surgical robot **11**, surgical tool **12** and pair of rails **14** to the computer **28** is different. The ultrasonic motors in each of the surgical robot **11**, surgical tool **12** and rails **14** are operably connected to a controller **32** (shown in FIGS. **5** and **6**) with cables **34**. The controllers **32** are in an electronic box **36**. The controllers **32** in the electronic box **36** are operably connected to the computer **28**. The electronic box is made of aluminum. The cables **34** are operably connected to a dedicated room ground **38** and filter **40**. The room ground **38** is connected to the MRI room wall **42**. The MRI machine **44** and robot **11** are situated inside the MRI room **46** and the electronic box **36** and the computer **28** are situated outside of the MRI room in a control room **48**. As is well known to those skilled in the art the MRI room is shielded to avoid RF noise. It will be appreciated by those skilled in the art that robot **11** is shown herein by way of example only and that other surgical robot that uses ultrasonic motors could also be used.

[0034] The connection for each ultrasonic motor **16** to the computer **28** is shown in FIG. **5** and the connection of a plurality of ultrasonic motors **16** to the computer **28** is shown in FIG. **6**. Controller **32** includes at least one encoder reader channel, at least one digital input port, at least two digital output port and at least one analog output port. It will be appreciated by those skilled in the art that since the controller includes at least one analog output the controller has a digital to analog converter included therein.

[0035] Preferably the controller includes a plurality of analog output ports, a plurality of encoder readers, and a plurality of digital output ports. By way of example the USB4™ produced by US Digital is used in controller **32**. The USB4™ includes four (4) channels of encoder readers, eight (8) digital outputs, four (4) analog outputs, eight (8) digital inputs, four (4) analog inputs. Each ultrasonic motor **16** of the surgical robot **30** uses one channel encoder reader, one analog output, one digital input and two digital output. Therefore four ultrasonic motors are controlled by one USB4™. Since the surgical robot **11** that is shown by way of example includes nine ultrasonic motors in the improved surgical robot system **30** described herein two USB4 controllers are used as well as a dedicated controller used in associated with one of the specific motor. Surgical robot **11** includes eight Shinsei Ultrasonic Motor and one Korean motor PUMR40E Model: PUMR40E-DN™ this motor has a dedicated controller which is housed in the electronic box **36**. The dedicated controller has similar features to those described above but for use with a single motor.

[0036] The USB4 is connected through a USB port with a PC. In practice the controller **32** or more specifically the USB4s and the dedicated Korean motor controller together with the computer **28** operate together to control the ultrasonic motors **16**. The USB4 and the dedicated Korean controller each provide an analog signal that controls the USM speed. In such configuration the USB4 and the PC operate together as the motor controller. It will be appreciated by those skilled in the art that the number of controllers **32** or controllers with a plurality of analog inputs will be determined by the number of motors in the surgical robot. Accordingly this may be scaled up or down depending on the number of motors.

[0037] The cables **34** connecting the motors **16** and encoders **18** to the motor drivers **20** are provided with RF shielding. By way of example, a tin copper tube sleeve **50** is used. As shown in FIG. **7**A there is a separate motor cable **52** that operably connects the US motor **16** to the controller and a separate encoder cable **54** that operably connects the encoder **18** to the controller **32**. A plurality of cables **34** may be bundled together in one tin copper tube sleeve **50** as shown in FIG. **7**B. It will be appreciated by those skilled in the art that alternate RF shielding materials could also be used. Tin copper shielding was chosen as it currently provides a good balance between shielding results and cost. The requirement of RF shielding material is that it must have good conductivity of electricity. Other alternatives would be copper, galvanized steel, silver or gold. However some of these options are unlikely due to the cost of materials. The tin-copper sleeve used herein by way of example is made up of a plurality of small tin copper wires that are coven together.

[0038] The electronic box **36** and the shielding tubes **50** are connected to the room ground **38**. It has been observed that the grounding significantly improves the effectiveness of the shielding provided by the tin copper tube sleeve **50**. Further it has been observed that the grounding of the shielding tubes and electronic box to the ground of a wall power outlet does not significantly reduce the RF noise. A dedicated ground **38** of the MRI room is used for grounding the shielding and electronic box.

[0039] It has been observed that typically MRI machines are sensitive to signals of a specific frequency range. For example, Philips 3.0T MR scanner is sensitive to 80 MHz and higher signals. A low pass filter **40** is added to reduce the noise at this and higher frequencies. A "low pass" filter is used such that only low frequency signals can pass. As is well known in the art MRI machines are very sensitive to their resonant frequency. Usually the resonant frequency for an MRI machine is between 60 and 80 Mhz.

[0040] Ideally the low pass filter **40** should eliminate any noise signal affecting the MRI machine resonant frequency. The cut off frequency of the low pass filter depends on the specific a MRI machine and noise level. Preferably the low pass filter **40** provides at least −20 DB reduction at the MRI resonant frequency. Preferably the cut off frequency of the low pass filter **40** is much lower than MRI resonant frequency. By way of example a SPECTRUM CONTROL-56-705-003-FILTERED D Sub-connector is used for filtering. This sub-connector has a built-in lowpass filter with the 3 DB cut off frequency at 3.2 MHz. The low pass filter **40** is operably connected the MRI dedicated room ground **38**.

[0041] Images obtained from an MR scanner show the surprising and significant improvement obtained with the improved surgical robot assembly **30**. More specifically FIGS. **8**A, **8**B and **8**C shows a sequence of MRI images of a piece of meat of a 2-D FGRE (fast gradient recalled echo sequences) (axial) taken using the prior art surgical robot, wherein FIG. **8**A is without the motor, FIG. **8**B is with the motor powered on without motion and FIG. **8**C is with the motor moving. These images clearly show that the prior art robot cannot be used concurrently with MR scanning.

[0042] FIGS. **9**A, **9**B, and **9**C is a sequence of MRI images of a piece of meat of a 2-D FSE T2 (fast spin echo with T2 weighting sequences) (axial) taken using the surgical robot with shielded cables, wherein FIG. **9**A is without the motor, FIG. **9**B is with the motor powered on without motion and FIG. **9**C is with the motor moving. FIGS. **10**A, **10**B, and **10**C show a sequence of MRI images of a piece of meat of a 2-D FGRE (axial) taken using the surgical robot with shielded cables, wherein FIG. **10**A is without the motor, FIG. **10**B is with the motor powered on without motion and FIG. **10**C is with the motor moving. These images clearly show that when the prior art robot assembly with new cable shielding of tin copper tube sleeve is used, by observation, the images in the FSE T2 sequences show images having small artifact and medium noise degradation and in the FGRE sequence images having medium artifact and large noise degradation.

[0043] FIGS. **11**A and **11**B shows a sequence of MRI images of a phantom of a 2-D FSE T2 (axial) taken using the surgical robot with a USB4 controller and shielded cables, wherein FIG. **11**A is without the motor and FIG. **11**B is with the motor moving. These images show medium artifact and large noise degradation.

[0044] In contrast the images shown in FIGS. **12** and **13** taken with the improved surgical robot **20** show little degradation. More specifically FIGS. **12**A and **12**B show a sequence of MRI images of a piece of meat of a 2-D FGRE (axial) taken using the improved surgical robot assembly of FIG. **3**, wherein FIG. **12**A is with the motor powered on without motion and FIG. **12**B is with the motor moving. FIGS. **13**A, **13**B and **13**C show a sequence of MRI images of a small watermelon of a 2-D FGRE (axial) taken using the improved surgical robot assembly of FIG. **3**, wherein FIG. **13**A is with the motor powered on without motion, FIG. **13**B is with the turret module of the surgical robot moving and FIG. **13**C is with surgical tool moving. By observation FIGS. **12** and **13** show that the quality of MR images appears not to be affected; that is, with reference to the images no significantly interfering frequencies were observed, other forms of noise were not observed, significant deterioration of the images was not observed, and image shifts were also not observed.

[0045] Generally speaking, the systems described herein are directed to surgical robots. Various embodiments and aspects of the disclosure will be described with reference to details discussed below. The following description and drawings are illustrative of the disclosure and are not to be construed as limiting the disclosure. Numerous specific details are described to provide a thorough understanding of various embodiments of the present disclosure. However, in certain instances, well-known or conventional details are not described in order to provide a concise discussion of embodiments of the present disclosure.

[0046] As used herein, the terms, "comprises" and "comprising" are to be construed as being inclusive and open ended, and not exclusive. Specifically, when used in the specification and claims, the terms, "comprises" and "comprising" and variations thereof mean the specified features, steps or components are included. These terms are not to be interpreted to exclude the presence of other features, steps or components.

[0047] As used herein, the term "exemplary" means "serving as an example, instance, or illustration," and should not be construed as preferred or advantageous over other configurations disclosed herein.

[0048] As used herein the "operably connected" or "operably attached" means that the two elements are connected or attached either directly or indirectly. Accordingly the items need not be directly connected or attached but may have other items connected or attached therebetween.

What is claimed is:

1. A surgical robot assembly for use with an MRI scanner that is housed in an MRI room comprising:

a surgical robot with at least one ultrasonic motor wherein all the motors therein are ultrasonic motors;

a controller spaced from the surgical robot and positioned outside the MRI room, the controller having at least one analog output, at least one digital input, at least two digital output, and at least one encoder reader channel;

cables operably attaching the motors of the surgical robot to the controller, the cables being RF shielded;

a dedicated room ground and the cables which are operably connected between the motors of the surgical robot and the controller are operably connected thereto; and

a filter operably connected to the cables which are operably connected between the motors of the surgical robot and the controller, the filter having a cut off frequency tuned to the MRI.

2. The surgical robot assembly of claim **1** wherein the surgical robot includes a plurality of motors and a plurality of encoders and the controller includes a plurality of analog outputs and a plurality of encoder reader channels and the plurality of motors and the plurality of encoders are operably attached to the same controller.

3. The surgical robot assembly of claim **2** wherein the controller is a USB4 controller.

4. The surgical robot assembly of claim **1** wherein the cables are shielded with copper tube sleeves.

5. The surgical robot assembly of claim **4** wherein the surgical robot includes a plurality of motors and a plurality of encoders and each motor has a cable between the motor and the controller and each encoder has a cable between the encoder and the controller and a plurality of cables are bundled together in a copper tube sleeve.

6. The surgical robot assembly of claim **5** wherein the plurality of motors are operably attached to the same controller.

7. The surgical robot assembly of claim **6** wherein the controller is a USB4 controller.

8. The surgical robot assembly of claim **1** wherein the dedicated ground is attached to the cables and attached to a wall of the MRI room.

9. The surgical robot assembly of claim **1** wherein the filter is a low pass filter.

10. The surgical robot assembly of claim **9** wherein the MR scanner is a Philips 3.0T MR scanner and the low pass filter has a 3 DB cut off frequency at 3.2 MHz.

11. The surgical robot assembly of claim **9** wherein the filter is a SPECTRUM CONTROL-56-705-003-FILTERED D Sub-connector.

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专利名称(译)	用于MRI的手术机器人系统		
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摘要(译)

用于MRI的手术机器人组件包括手术机器人，控制器，线缆，专用房间地面和过滤器。手术机器人包括至少一个超声波马达，其中的所有马达都是超声波马达。控制器与手术机器人间隔开并且位于MRI室外部。控制器至少有一个模拟输出;至少一个数字输入，至少两个数字输出和至少一个编码器读取器通道。电缆可操作地将手术机器人的马达连接到控制器并且是RF屏蔽的。电缆可操作地连接到专用房间地面。过滤器可操作地连接到电缆，电缆可操作地连接在手术机器人的电动机和控制器之间，并且过滤器具有调谐到MRI的截止频率。