User Guide

Project: The da Vinci Research Kit

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Figures and Table list

Introduction

The *da Vinci*® Surgical System integrates 3D endoscopy and state-of-the-art robotic technology to virtually extend the surgeon's eyes and hands into the surgical field, thus enhancing minimally-invasive access for complex surgical procedures. Figure 1 illustrates the three main physical components of the system, including a Surgeon's Console, a Patient-side Cart with four interactive robotic arms, and a Vision Cart. The surgeon interacts with a pair of Master Tool Manipulators (MTMs) located within the Surgeon’s Console in order to control the four robotic manipulators that are mounted to the Patient-side Cart. These include three Patient-Side Manipulators (PSMs) for manipulating Endo-Wrist instruments, and one Endoscope Control Manipulator (ECM), which carries the stereo endoscope instrument.

FIGURE 1: THE *DA VINCI STANDARD* SURGICAL SYSTEM WHILE IT IS OPERATING.

To support research in the field of telerobotic surgery, Intuitive Surgical is providing a research kit—also known as the “da Vinci Research Kit”, as a development platform for researchers to build upon. The hardware that we are providing as part of this kit includes the following components from our first-generation da Vinci system:

- One pair of Master Tool Manipulators (MTM)
- One pair of Patient Side Manipulators (PSM)
- One Foot Pedal Tray
- One High Resolution Stereo Viewer (HRSV)
- Four da Vinci Manipulator Interface Boards (dMIB)
- Essential instruments and accessories.

Some users may have a complete da Vinci system that includes additional components, in particular:

- A third PSM.
- One Endoscopic Camera Manipulator (ECM).
- A vision system.

- Patient-side cart with setup structure and setup joints.

This document will cover the basics of each of the individual components in the kit, with details of how to interface and use the hardware in your projects. Note that there is no software included with this kit…that part is up to you! Nevertheless, we do attempt to provide some of the key inputs and parameters that you will need to write your software and control systems.

Master Tool Manipulator

The MTMs are masters used to remotely teleoperate the slaves, such as the PSMs and ECM. There are two MTMs provided with the kit—the Left MTM and the Right MTM. The two MTMs are identical to each other in every aspect except for their wrists, which are mirror images of each other. The MTM is an 8-DOF manipulator with the first seven joints actuated. Each joint is instrumented with a pair of joint angle sensors. The MTMs are typically operated under gravity compensation and the motion commands driven by the user are tracked and used to control the slaves.

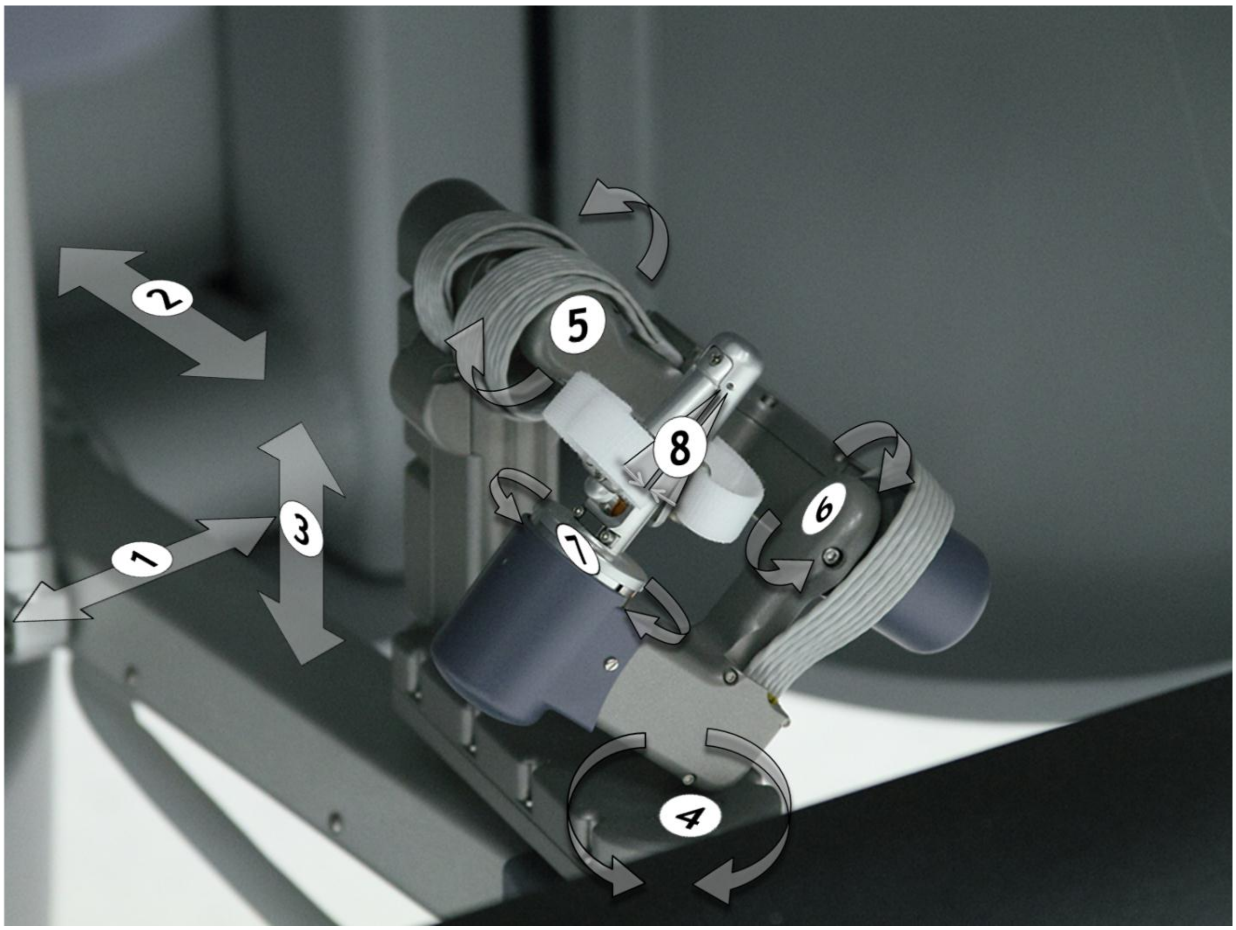


FIGURE 2: THE JOINTS OF THE MTM AND THEIR DIRECTION OF MOTION.

The MTMs have eight joints. The direction of motion that each joint produces is illustrated in Figure 2. The numbers in the figure refer to the joints described in Table 1.

TABLE 1: SUMMARY OF MTM JOINTS.

MTM Joint	Joint type*	Joint Name	Description
1	1	Outer Yaw	This joint moves the entire MTM about the mounting base. The axis of rotation is perpendicular to the ground.
2	1	Outer Pitch1 (Shoulder)	This joint is one of the two joints that are responsible for the pitch and in/out translation of the MTM.
3	1	Outer Pitch2 (Elbow)	This joint is the second of the joint pair which together with the previous joint controls the pitch and in/out translation of the MTM.
4	1	Setup Joint (Platform)	This joint acts as the platform for the Gimbal arrangement for the MTM's wrist; it also provides the extra degree of freedom to enable movement in the NULL space.
5	1	Wrist Pitch	This joint determines the pitch of the wrist in the gimbal arrangement.
6	1	Wrist Yaw	This joint determines the yaw of the wrist in the gimbal arrangement.
7	1	Wrist Roll	This joint determines the roll of the wrist in the gimbal arrangement.
8	1	Finger Grips	This joint directly controls the desired motion of the jaws of the instruments.
			Sections 4 to 8 constitute the Gimbal arrangement.

* 0 – No joint
1 – Revolute joint
2 – Prismatic joint

MTM kinematics

This section describes the kinematics of the MTM using the Denavit-Hartenberg (DH) convention. The DH convention used here is as follows:

We attach the coordinate frames to the mechanism in a manner such that moving from one frame to the next higher frame (towards the tip) involves first translating and rotating about the X axis, then translating and rotating about the Z axis. In other words, the frame whose Z axis describes a particular joint is attached to the distal link at that joint (towards the tip).

Therefore, if

R_n Describes the orientation of frame *n.*
c_n Defines the center (location) of frame *n.*
T_n Defines a transform representing $[c_n\ R_n]$

with ‘*n*’ increasing toward the mechanism tip/end-effector, and if the DH parameters are:

- ‘a’ – representing the movement along the X axis relative to the current frame,
- ‘α’ – representing the rotation about the X axis relative to the current frame,
- ‘D’ – representing the movement along the Z axis relative to the current frame,
- ‘θ’ – representing the rotation about the Z axis relative to the current frame,

then

$$R_{n+1} = R_n \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & -\sin(\alpha) \\ 0 & \sin(\alpha) & \cos(\alpha) \end{bmatrix} \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{n+1} = c_n + a \cdot x_n + d \cdot z_{n+1}$$

Figure 3 shows the MTM coordinate frames selected as per the DH convention mentioned above.

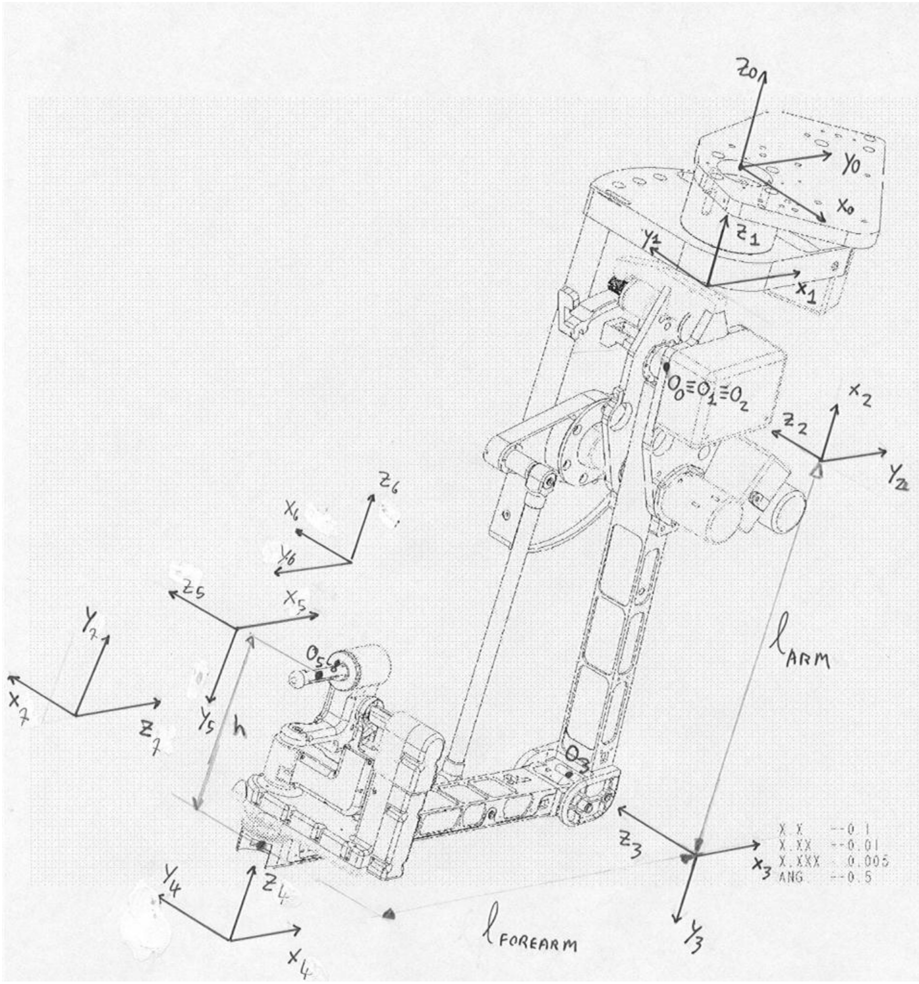


FIGURE 3: MTM WITH DH FRAMES.

TABLE 2: DH PARAMETER TABLE OF MTM.

Frame	Joint Name	Joint type	a	α	D	θ
1	Outer Yaw	1	0	0	0	$q_1 + \frac{\pi}{2}$
2	Outer Pitch1 (Shoulder)	1	0	$-\frac{\pi}{2}$	0	$q_2 - \frac{\pi}{2}$
3	Outer Pitch2 (Elbow)	1	$-l_{arm}$	0	0	$q_3 - q_2$
	Forearm	0	$-l_{forearm1}$	0	0	0
4	Setup Joint (Platform)	1	$-l_{forearm2}$	$\frac{\pi}{2}$	h	q_4
5	Wrist Pitch	1	0	$-\frac{\pi}{2}$	0	q_5
6	Wrist Yaw	1	0	$\frac{\pi}{2}$	0	$q_6 + \frac{\pi}{2}$
7	Wrist Roll	1	0	$\frac{\pi}{2}$	l_4	q_7

The constants and variables referenced in Table 2 are:

$$l_{arm} = 0.2794\ m$$
$$l_{forearm1} = 0.3048\ m$$
$$l_{forearm2} = 0.0597\ m$$
$$h = 0.1506\ m$$
$$q_1\ to\ q_7\ are\ the\ joint\ variables$$

Actuation

The parallel actuation system of joint 2 and 3 (shoulder and elbow) creates the following coupling between joint variables (q_x) and motor variables (q_{mx}):

$$q_{m2} = n_{t2} q_2$$
$$q_{m3} = n_{t3}(q_3 + q_2)$$
$$Q_{m4} = n_{t4}\left(q_4 + \frac{r_{43}}{r_{44}} q_3\right)$$

with n_{tx} being the transmission ratio (gear ratio) induced by the x^{th} actuation and transmission system, r_{43}being the radius of the idler pulley on the joint 3 rotation axis and r_{44}being the radius of the drive pulley of the joint 4 cable transmission. The joint variables are computed from the motor variables as follows:

$$q_2 = \frac{q_{m2}}{n_{t2}}$$
$$q3 = \frac{q_{m3}}{n_{t3}} - \frac{q_{m2}}{n_{t2}}$$
$$q_4 = \frac{q_{m4}}{n_{t4}} - \frac{r_{43}}{r_{44}}\left(\frac{q_{m3}}{n_{t3}} - \frac{q_{m2}}{n_{t2}}\right)$$

The associated relationship between motor torques $\tau_{mi}$and joint torques τ is:

$$\tau_{m2} n_{t2} = \tau_2 - \tau_3 + \frac{r_{43}}{r_{44}} \tau_4$$
$$\tau_{m3} n_{t3} = \tau_3 - \frac{r_{43}}{r_{44}} \tau_4$$
$$\tau_{m4} n_{t4} = \tau_4$$

For the Master Tool Manipulator, we have (in inches!):

$$r_{43} = 0.5515$$
$$r_{44} = 0.8235$$

These relations and equations can be used to arrive at the motor torques required.

MTM hardware

The MTMs have actuators, encoders and sensors for each joint of the manipulator for providing feedback and actuation. Table 3 summarizes the components of each section in the MTM.

TABLE 3: SUMMARY OF KEY HARDWARE COMPONENTS IN EACH SECTION OF MTM.

Joints	Actuator	Encoder	Potentiometer	Differential line driver Board	Hall effect Sensor
Outer Yaw	1 Maxon DC motor RE-025-055-38	1000 lines HP HEDM-5500-B02	5 K rotary linear POT	RS 422 IC AM26C31	
Outer Pitch1 (Shoulder)	1 Maxon DC motor RE-025-055-38	1000 lines HP HEDM-5500-B02	5 K rotary linear POT	RS 422 IC AM26C31	
Outer Pitch2 (Elbow)	1 Maxon DC motor RE-025-055-38	1000 lines HP HEDM-5500-B02	5 K rotary linear POT	RS 422 IC AM26C31	
Setup Joint (Platform)	1 Maxon DC motor RE-025-055-38	1000 lines HP HEDM-5500-B02	5 K rotary linear POT	RS 422 IC AM26C31	
Wrist Pitch	1 Maxon DC motor RE-013-032-06	16 counts DME* on motor	4.5 K rotary linear POT	Three RS 422 IC AM26C31 on a single board	
Wrist Yaw	1 Maxon DC motor RE-013-032-06	16 counts DME* on motor	4.5 K rotary linear POT		
Wrist Roll	1 Maxon DC motor RE-013-020-08	16 counts DME* on motor	4.5 K rotary linear POT		
Finger Grips					Two A3507 linear Hall sensor

* DME – Digital Magnetic Encoder

The joints 1 to 7 have incremental quadrature encoders and the outputs from these encoders are converted to RS422 format by using a differential line driver chip. The first 4 joints have independent differential line driver boards, while the sections of the wrist or the gimbal unit has a single shared differential line driver board. The potentiometers present at each joint are used as additional feedback for the motors of the respective joints. It is important to note that the encoder and potentiometer are linked to the drivetrain differently. The encoders are mounted to the motor shafts, whereas the potentiometers are either cable or gear driven from the joint output side. The finger gripper section has two Hall Effect sensors and a permanent magnet assembled such that it can measure the position or the extent to which the finger grips are pressed.

Figure 4 and Figure 5 show the physical locations of the components in the MTM.

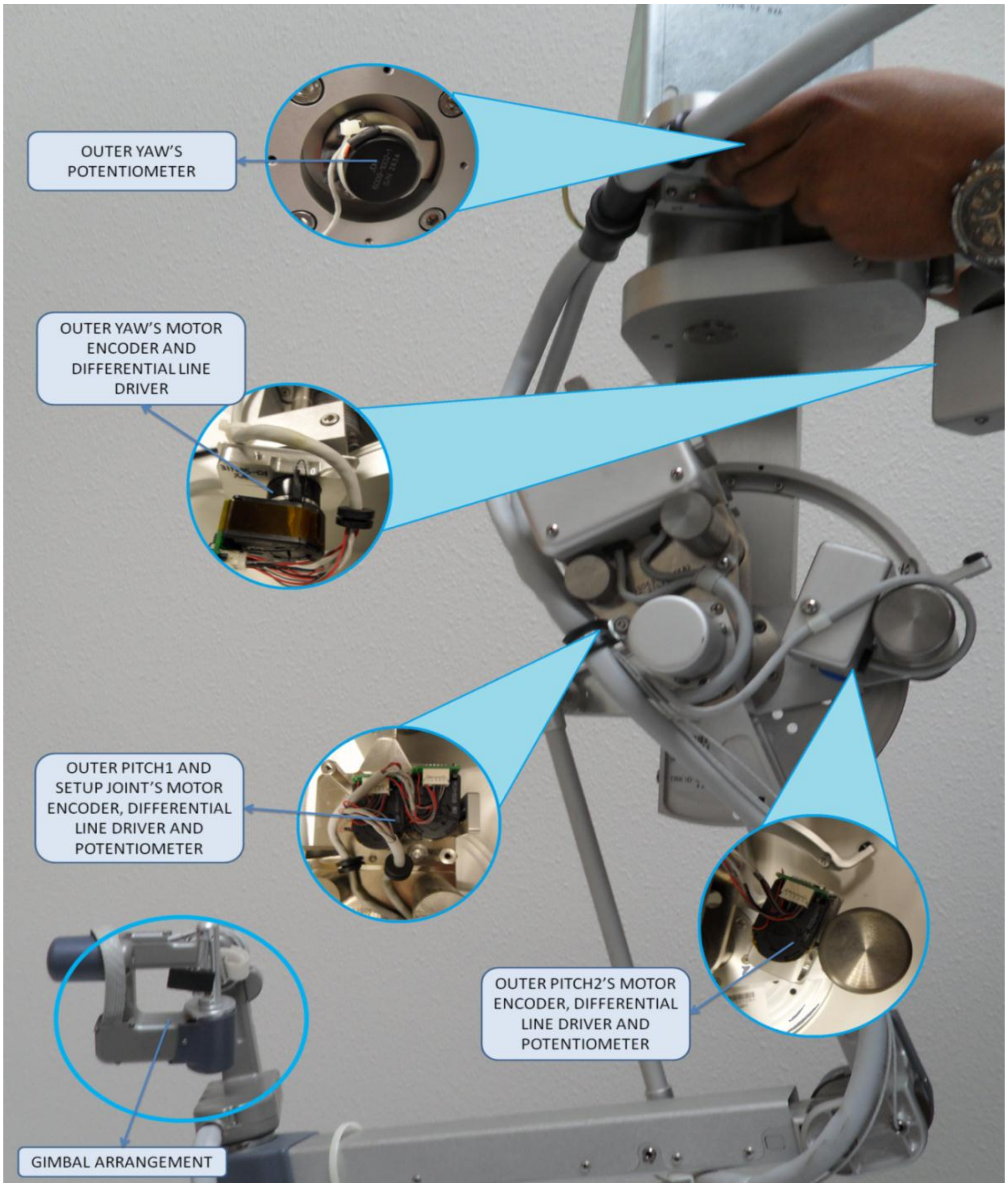


FIGURE 4: MTM WITH COMPONENT PLACEMENT.

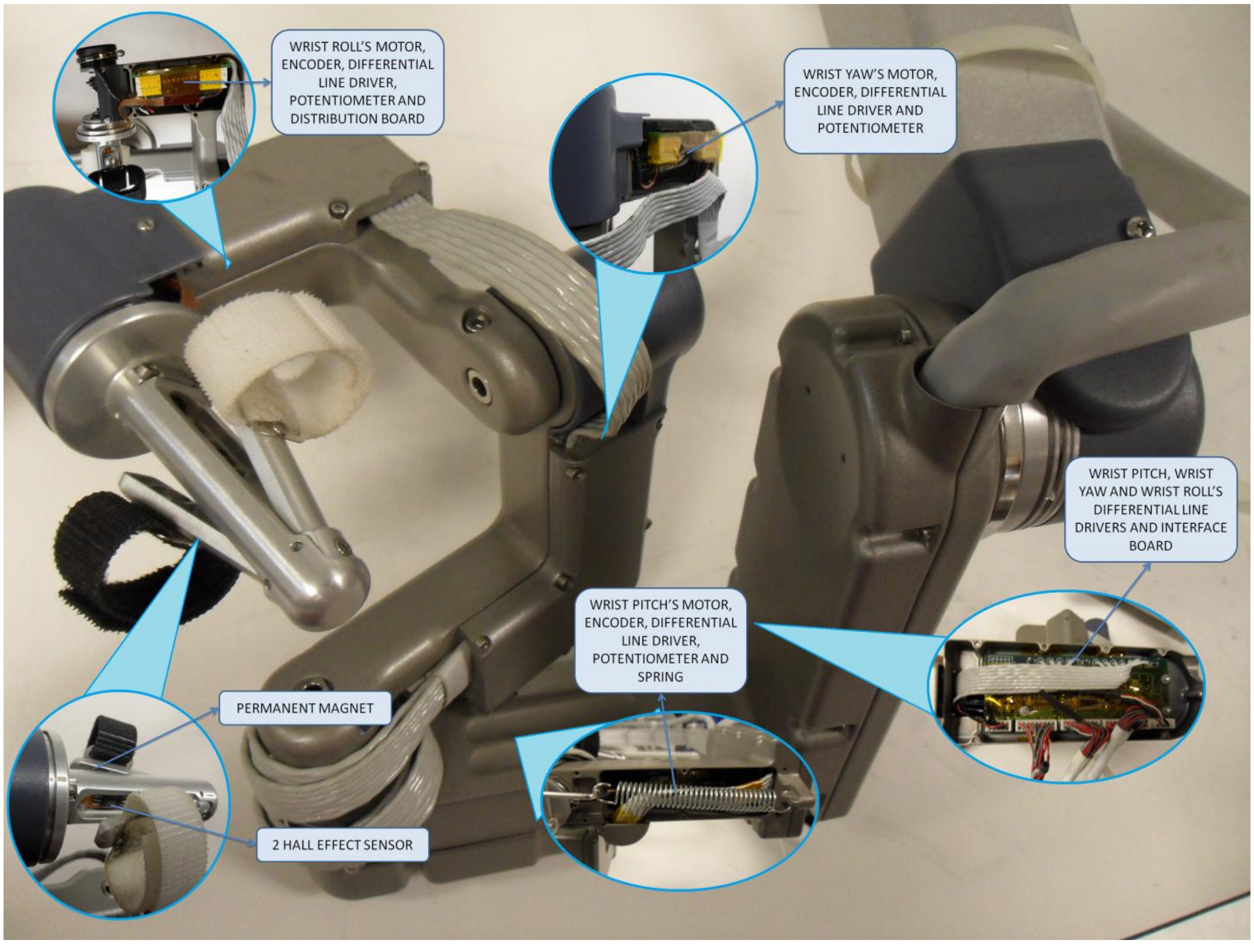


FIGURE 5: GIMBAL ARRANGEMENT COMPONENT PLACEMENT.

Table 4 summarizes the default and the actual operating conditions of the MTM motors used in the da Vinci system.

TABLE 4: MTM ACTUATOR OPERATING CONDITIONS.

#	Axis	Motor Type	Default Max.		Actual Max. Current		Torque Constant	Max. Torque	Gear Ratio*	Encoder
			Voltage (V)	Current (A)	(%)	(Amp)	(Nm/A)	(Nm)		Counts/Rev
1	Outer Yaw	RE025-055-38	24	0.670	100	0.670	0.043800	0.0293	63.41	4000.00
2	Shoulder	RE025-055-38	24	0.670	100	0.670	0.043800	0.0293	49.88	4000.00
3	Elbow	RE025-055-38	24	0.670	100	0.670	0.043800	0.0293	59.73	4000.00
4	Platform	RE025-055-38	24	0.670	137	0.920	0.043800	0.0403	10.53	4000.00
5	Wrist Pitch– **High**	RE013-032-06	9	0.590	161	0.950	0.004950	0.0047	33.16	64.00
5	Wrist Pitch– **Continuous**	RE013-032-06	9	0.590	132	0.780	0.004950	0.0039	33.16	64.00
5	Wrist Pitch- **Low**	RE013-032-06	9	0.590	127	0.750	0.004950	0.0037	33.16	64.00
6	Wrist Yaw	RE013-032-06	9	0.590	100	0.590	0.004950	0.0029	33.16	64.00
7	Wrist Roll	RE013-020-08	6	0.407	100	0.407	0.003390	0.0014	16.58	64.00

* Gear Ratio – the gain from the motor shaft to the actual joint.

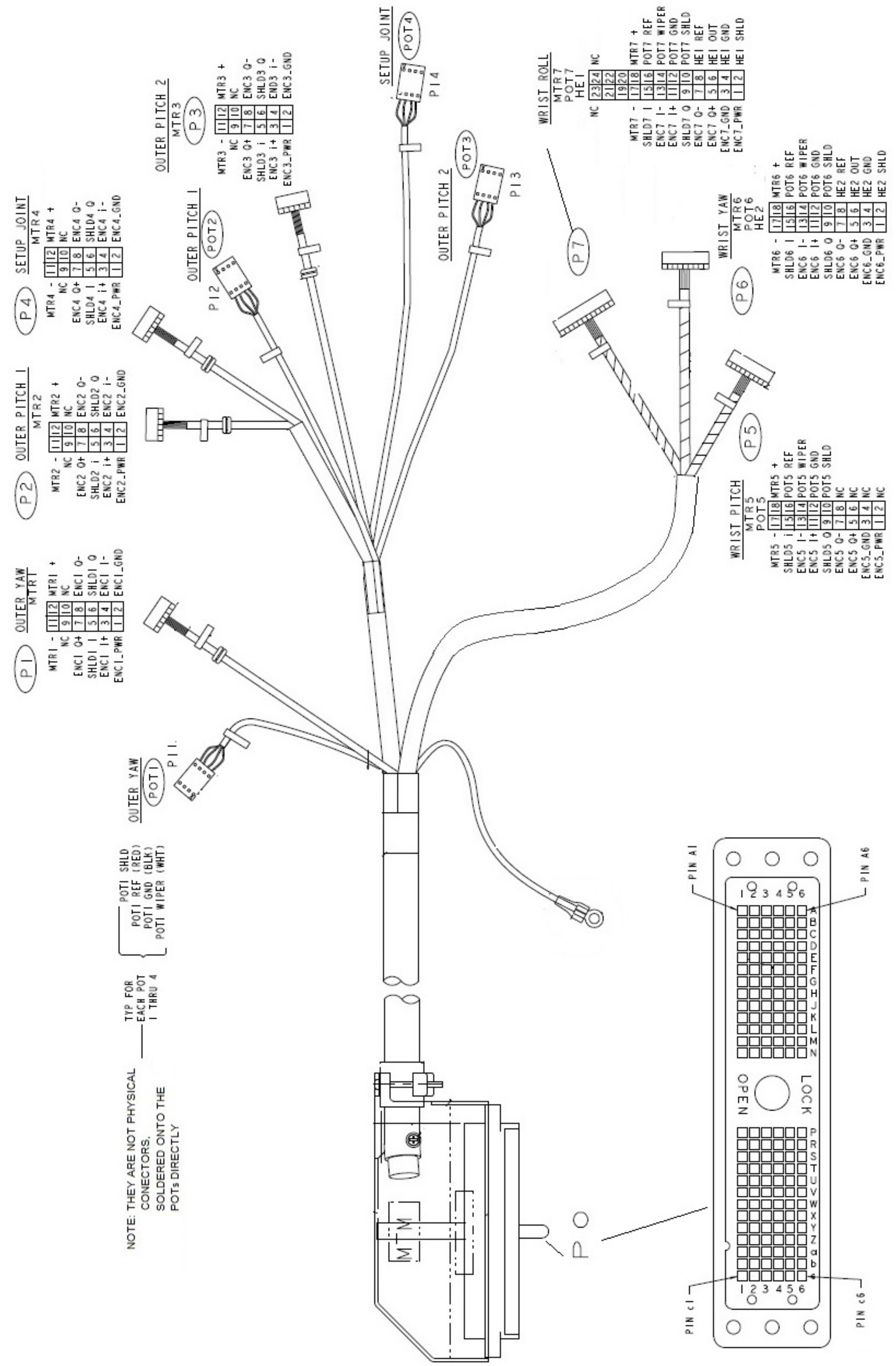


FIGURE 6: MTM INTERFACE CONNECTOR WIRING LAYOUT.

The interface to all the electronics and electrical components in the MTM is through a single Zero Insertion Force DL156 pin connector from ITT Canon. Figure 6 shows the layout of the wiring of the connector. P0 is the main interface connector and P1 to P14 are the connectors that go to various sections of the MTM. The pinouts of the P0 interface connector is detailed in APPENDIX A.

MTM calibration

The calibration files contain values for several of the physical parameters of the MTM; these will be useful for transforming from raw sensor data to joint space or configuration space. This section explains those parameters and how to use them.

The MTM calibration files have of the various parameters, such as the limits of the joints and potentiometers.

Below is **an example** of a section of a calibration file to elaborate on the relevant parameters (please see the calibration files that came with your Research Kit for the numbers specifically for your hardware).

```
////////////////////////////////////////////////////////////////////////////////////////////////////
////////////////////////////////////////
serial_number:
25348
joint_range_upper_limit:
0.783 1.1633 0.73519 3.5997 3.2763 0.8194 7.899
joint_range_lower_limit:
-1.277 -0.3522 -0.24167 -1.6799 -1.7055 -0.8194 -8.3786
pot_input_gain:
0.0014424 0.0014267 0.0014378 -0.0014556 0.0015147 0.0015262 0.00077145
pot_input_offset:
-3.0564 -2.4432 -2.5923 3.8559 -2.346 -2.8235 -1.8213
pot_lower_limit:
2661 2530 2297 172 3688 2380 4096
pot_upper_limit:
1233 1468 1182 3799 399 1307 0
////////////////////////////////////////////////////////////////////////////////////////////////////
////////////////////////////////////////
```

Each of the above rows has eight columns corresponding to the eight joints separated by spaces:

- **joint_range_lower_limit** and **joint_range_upper_limit** are the physical joint limits represented in radians as per the DH convention.
- **pot_input_gain** is the gain to transform from the potentiometer 12-bit ADC value to the joint angle in radians.

- **pot_input_offset** is the offset measured in radians to map the angle measured from the potentiometer to the joint angle as per DH convention.
- **pot_lower_limit** and **pot_upper_limit** are 12-bit ADC values of the joint limits obtained by measuring the voltage across the wiper and ground terminal of the corresponding potentiometer (value of 0 represents 0V and 4096 represents full reference voltage, typically 5V).
- Column 8 of the potentiometer-parameters is not applicable.

Therefore, the actual joint angle can be calculated using the following formula**:**

$$\boldsymbol{Joint\ angle = pot\_input\_gain * pot\_adc\_value\ \ + pot\_input\_offset}$$

The second section of the **example** calibration file contains parameters like the following
///

```
gripsens.adc_open          = [   2180   ]
gripsens.adc_bumper         = [   2521   ]
gripsens.adc_closed         = [   3346.5 ]
gripsens_backup.adc_open      = [   2136.6 ]
gripsens_backup.adc_bumper    = [   2503.7 ]
gripsens_backup.adc_closed    = [   3448.2 ]
.....
....
..
```

///

The gripsens.adc_open/bumper/closed are 12 bit ADC values representing the output from the hall effect sensor at various states open/bumper/closed. Each MTM has two Hall Effect sensors hence two sets of values for gripsens.

Patient Side Manipulator

The PSMs are the slaves that will be teleoperated by the MTMs. Two identical PSMs are provided with the kit. Each PSM is a 7-DOF actuated manipulator, again with joint sensors and actuators for control purposes. They manipulate the attached instruments about the remote center (the mechanically-fixed fulcrum point that is invariant to the configuration of the joints of the PSM).

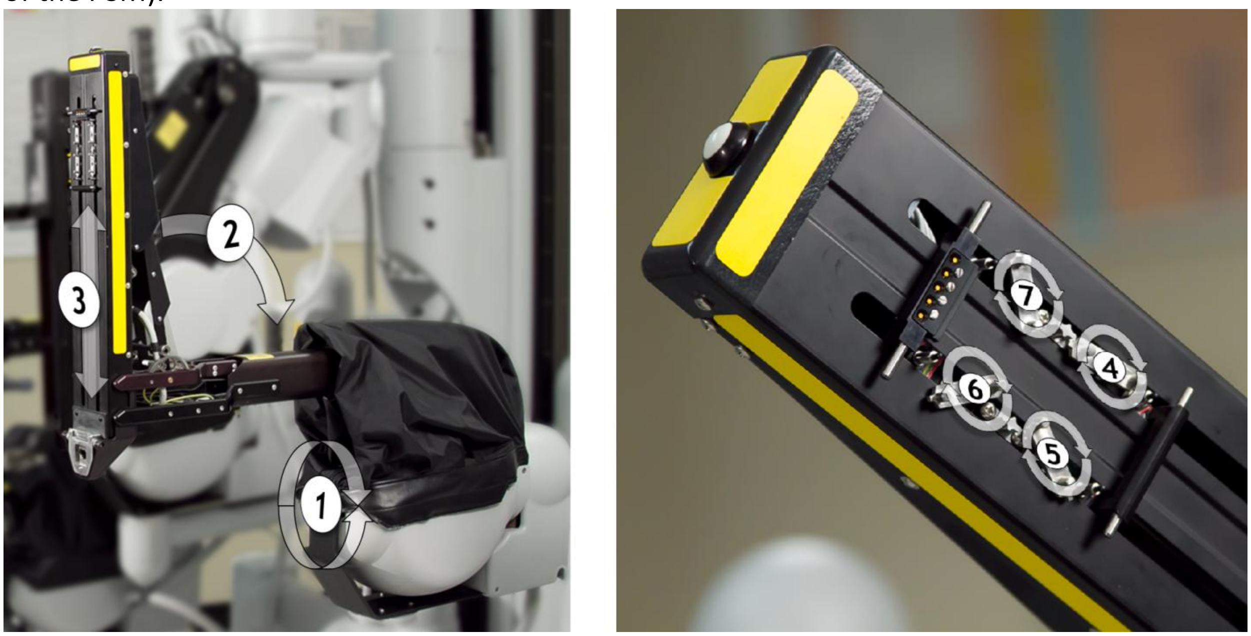


FIGURE 7: JOINTS OF THE PSM AND THEIR DIRECTION OF MOTION.

The PSMs contain 7 joints. The directions of motion of the 7 joints are illustrated in Figure 7. The numbers in the figure represent the sections as detailed in Table 5.

TABLE 5: SUMMARY OF PSM SECTIONS.

MTM Joint	Joint type*	Joint Name	Description
1	1	Outer Yaw	This is the only joint that moves the entire PSM with respect to its mounting base. It pivots the instrument in a yaw motion about the remote center. Home position (zero joint-angle) is center range of motion, which makes the insertion axis perpendicular to the PSM mounting plate.
2	1	Outer Pitch	This joint pivots the instrument in a pitching motion about the remote center. Home position (zero joint-angle) is chosen to make the insertion axis perpendicular to the PSM mounting plate, which it turns out is not quite center range of motion,
3	2	In/Out or Insertion	This axis moves the instrument along the axis of its shaft into or out of the patient. Home position (zero joint angle) is fully retracted, with the instrument’s control point located at the remote center.

MTM Joint	Joint type*	Joint Name	Description
4	1	Outer Roll	This axis rolls the instrument shaft. Home position (zero joint-angle) is center range of motion.
5	1	Wrist Pitch	This axis is the first (proximal) axis on the wrist mechanism (for standard 8mm instruments). Anthropomorphic to a human wrist knocking on a door. da Vinci does not home with instruments installed, so home is not defined in motor space. However, the zero joint-angle corresponds to a straight wrist.
6	1	Wrist Yaw 1	This axis is the second (more distal) axis on the wrist mechanism (for standard 8mm instruments). Anthropomorphic to a human wrist wiping a surface. It is a coordinated motion of two mechanical joints representing the two grippers. da Vinci does not home with instruments installed, so home is not defined for instruments. However, the zero joint-angle corresponds to a straight wrist.
7	1	Wrist Yaw 2	This joint is controlled in combination with Wrist Yaw 1 to effect wrist yaw and jaw open and close actuation.

* 0 – No joint
1 – Revolute joint
2 – Prismatic joint

Note that motors five, six and seven are coupled nontrivially with joints 5, 6, and 7, and control the Endo-Wrists of the instruments attached to the PSMs. This coupling is described in APPENDIX C. The PSM has a remote center location that is invariant to any joint movement. Figure 8 shows the remote center.

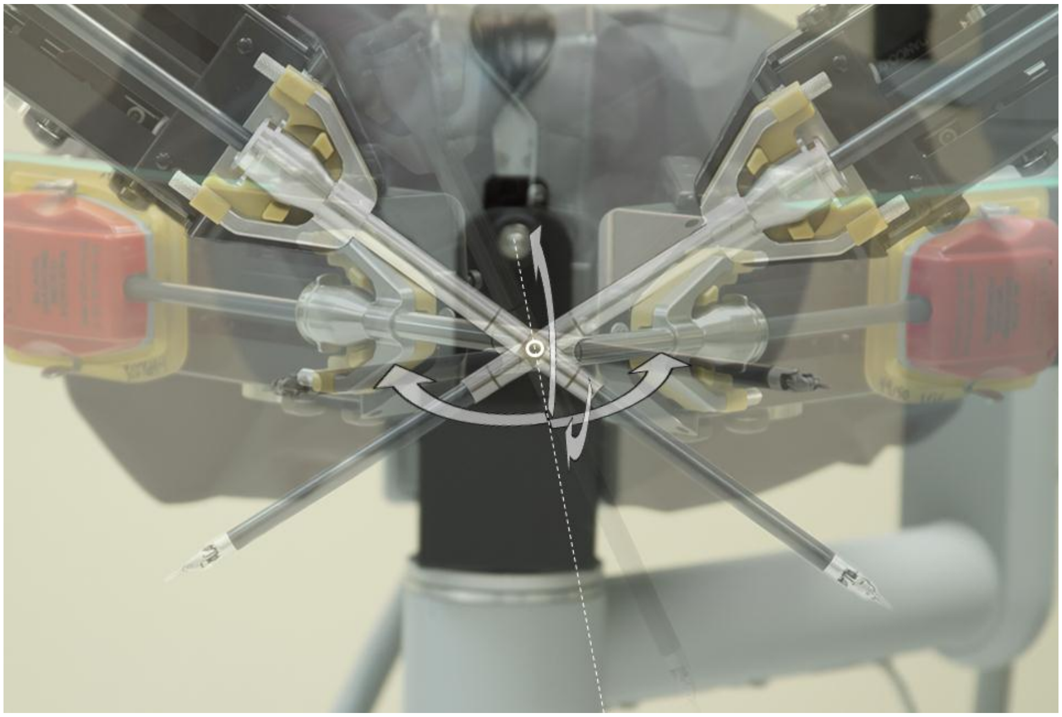


FIGURE 8: ILLUSTRATION OF REMOTE CENTER OF PSM

PSM kinematics

This section describes the kinematics of the PSM using the Denavit–Hartenberg (DH) convention or representation. The DH convention used here is as follows.

We attach the coordinate frames to the mechanism in a manner such that moving from one frame to the next higher frame (towards the tip) involves first translating and rotating about the X axis, then translating and rotating about the Z axis. In other words, the frame whose Z axis describes a particular joint is attached to the distal link at that joint (towards the tip).

Therefore, if

R_n describes the orientation of frame n
c_n defines the center (location) of frame n
T_n defines a transform representing $[c_n \; R_n]$

with 'n' increasing toward the mechanism tip/end-effector, and if the DH parameters are:

- 'a' – represents the movement along the X axis relative to the current frame,
- 'α' – represents the rotation about the X axis relative to the current frame,
- 'D' – represents the movement along the Z axis relative to the current frame,
- 'θ' – represents the rotation about the Z axis relative to the current frame,

then

$$R_{n+1} = R_n \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & -\sin(\alpha) \\ 0 & \sin(\alpha) & \cos(\alpha) \end{bmatrix} \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{n+1} = c_n + a \cdot x_n + d \cdot z_{n+1}$$

Here we assume the “Large Needle Driver” instrument is installed on the PSM. Figure 9 shows the coordinate frames selected as per the DH convention mentioned above.

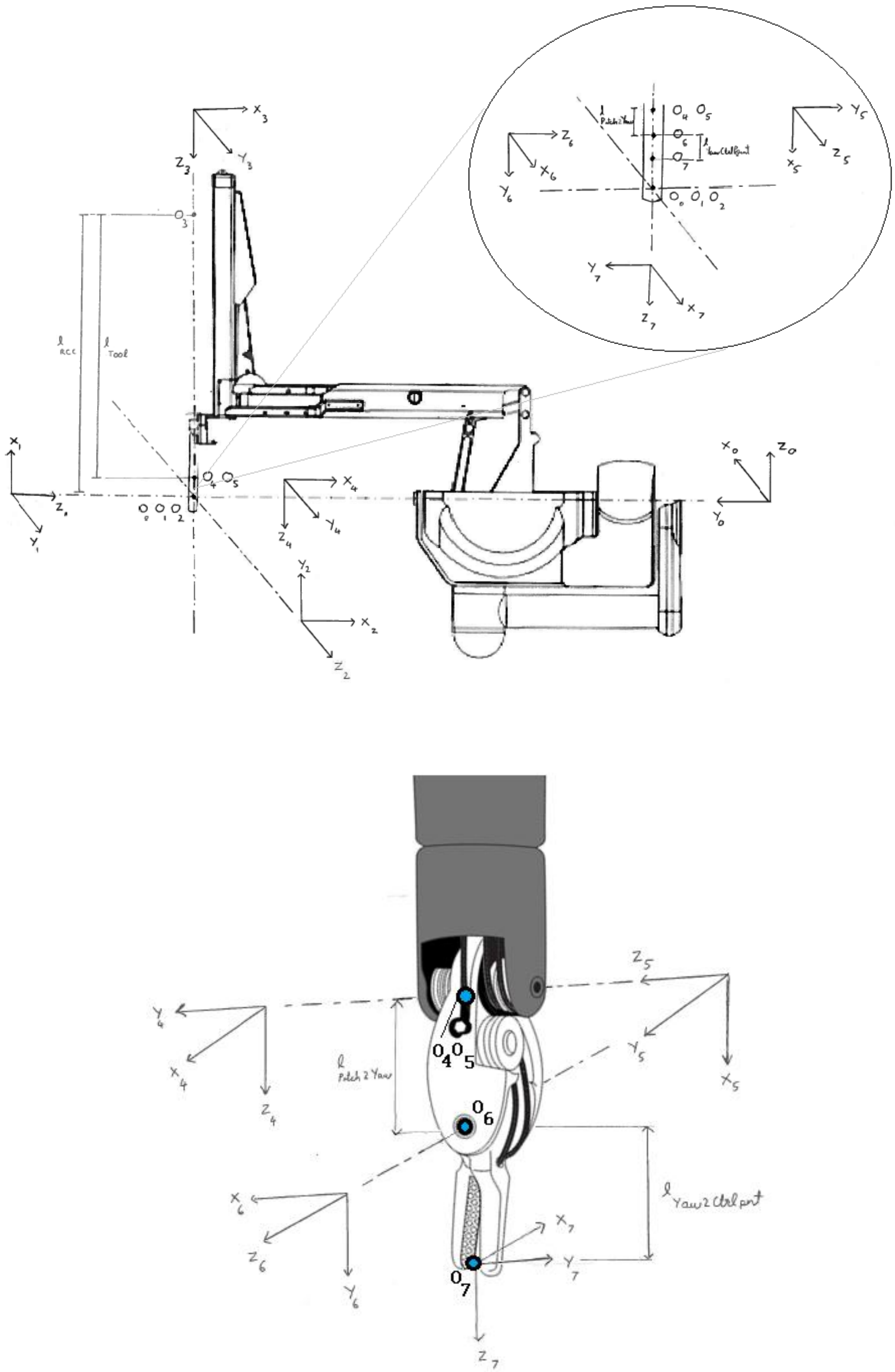


FIGURE 9: PSM WITH DH FRAMES. TOP: COMPLETE DH. BOTTOM: INSTRUMENT DH.

TABLE 6: DH PARAMETER TABLE FOR PSM

Frame	Joint Name	Joint type	a	α	D	θ
1	Outer Yaw	1	0	$\frac{\pi}{2}$	0	$q_1 + \frac{\pi}{2}$
2	Outer Pitch	1	0	$-\frac{\pi}{2}$	0	$q_2 - \frac{\pi}{2}$
3	In/out or Insertion	2	0	$\frac{\pi}{2}$	$q_3 - l_{RCC}$	0
4	Outer Roll	1	0	0	l_{tool}	q_4
5	Wrist Pitch	1	0	$-\frac{\pi}{2}$	0	$q_5 - \frac{\pi}{2}$
6	Wrist Yaw	1	$l_{Pitch2Yaw}$	$-\frac{\pi}{2}$	0	$q_6 - \frac{\pi}{2}$
7	End Effector	0	0	$-\frac{\pi}{2}$	$l_{Yaw2Ctrlpnt}$	0

The values for the geometric parameters of the PSM mentioned in Table 6 are:

$$l_{RCC} = 0.4318\ m$$
$$l_{tool} = 0.4162\ m$$
$$l_{Pitch2Yaw} = 0.0091\ m$$
$$l_{Yaw2CtrlPnt} = 0.0102\ m$$
$$q_1\ to\ q_6\ are\ the\ joint\ variables$$

PSM hardware

The PSMs have actuators, encoders and sensors for each manipulator joint for providing feedback and actuation. Table 7 summarizes the components of each joint of the PSM.

TABLE 7: SUMMARY OF KEY HARDWARE COMPONENTS IN EACH SECTION OF PSM.

Joints	Actuator	Encoder	Potentiometer	Differential line driver Board	Clutch switch
Outer Yaw	2 Maxon DC motor RE-025-055-38	3600 lines Canon TR36 LRE*	5 K rotary linear POT	RS 422 IC AM26C31	
Outer Pitch	2 Maxon DC motor RE-025-055-38	3600 lines Canon TR36 LRE*	5 K rotary linear POT	RS 422 IC AM26C31	DPST – NO & NC Tactile switch
In/out or Insertion	1 Maxon DC motor RE-025-055-38	3600 lines Canon TR36 LRE*	5 K rotary linear POT	RS 422 IC AM26C31	SPST - NO Tactile switch
Outer Roll	1 Maxon DC motor RE-025-055-38	1000 lines HP HEDM-5500-B02	5 K rotary linear POT	RS 422 IC AM26C31	
Wrist Pitch	1 Maxon DC	1000 lines	5 K rotary	RS 422 IC	

Joints	Actuator	Encoder	Potentiometer	Differential line driver Board	Clutch switch
	motor RE-025-055-38	HP HEDM-5500-B02	linear POT	AM26C31	
Wrist Yaw 1	1 Maxon DC motor RE-025-055-38	1000 lines HP HEDM-5500-B02	5 K rotary linear POT	RS 422 IC AM26C31	
Wrist Yaw 2	1 Maxon DC motor RE-025-055-38	1000 lines HP HEDM-5500-B02	5 K rotary linear POT	RS 422 IC AM26C31	

* LRE – Laser Rotary Encoder

The joints 1 & 2 have two DC motors per joint arranged in parallel to have a higher torque output. The encoders used are incremental quadrature encoders and the outputs from the encoders are converted to RS422 format by using a differential line driver chip. Each encoder has its own independent differential line driver board. The potentiometers present in each joint are used as additional feedback for the motors of each joint. It is important to note that the encoder and potentiometer are linked to the drivetrain differently. The encoders are mounted to the motor shaft, whereas the potentiometers are either cable or gear driven at the joint output side. There are two clutch or brake release switches present on the PSM that can be used to engage clutching of the manipulators (by clutching we mean floating the joints so that they can be back-driven). Figure 10 shows the physical location of the key components of the PSM.

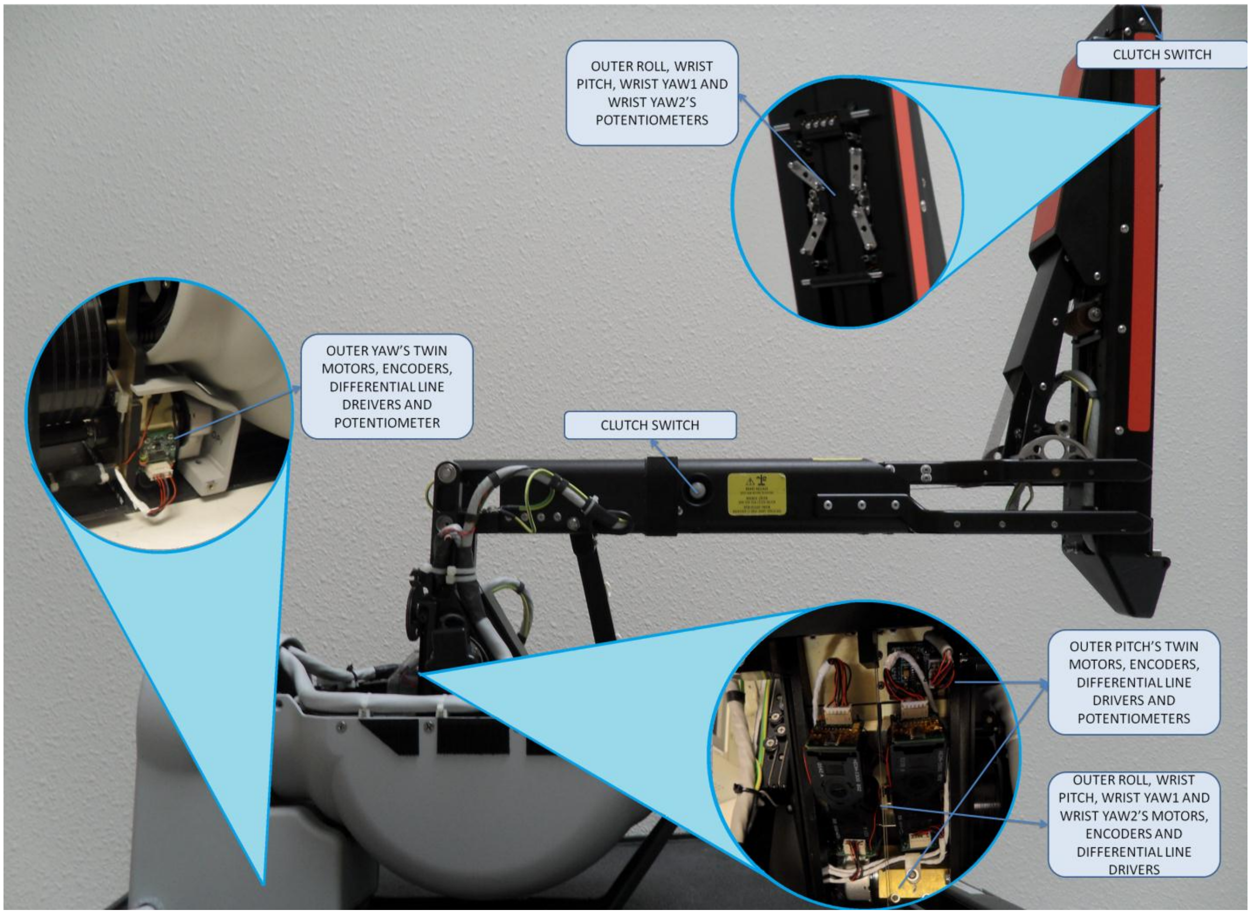


FIGURE 10: PSM WITH COMPONENT PLACEMENT.

Table 8 summarizes the default and the actual operating conditions of the motors used in the 'da Vinci' system.

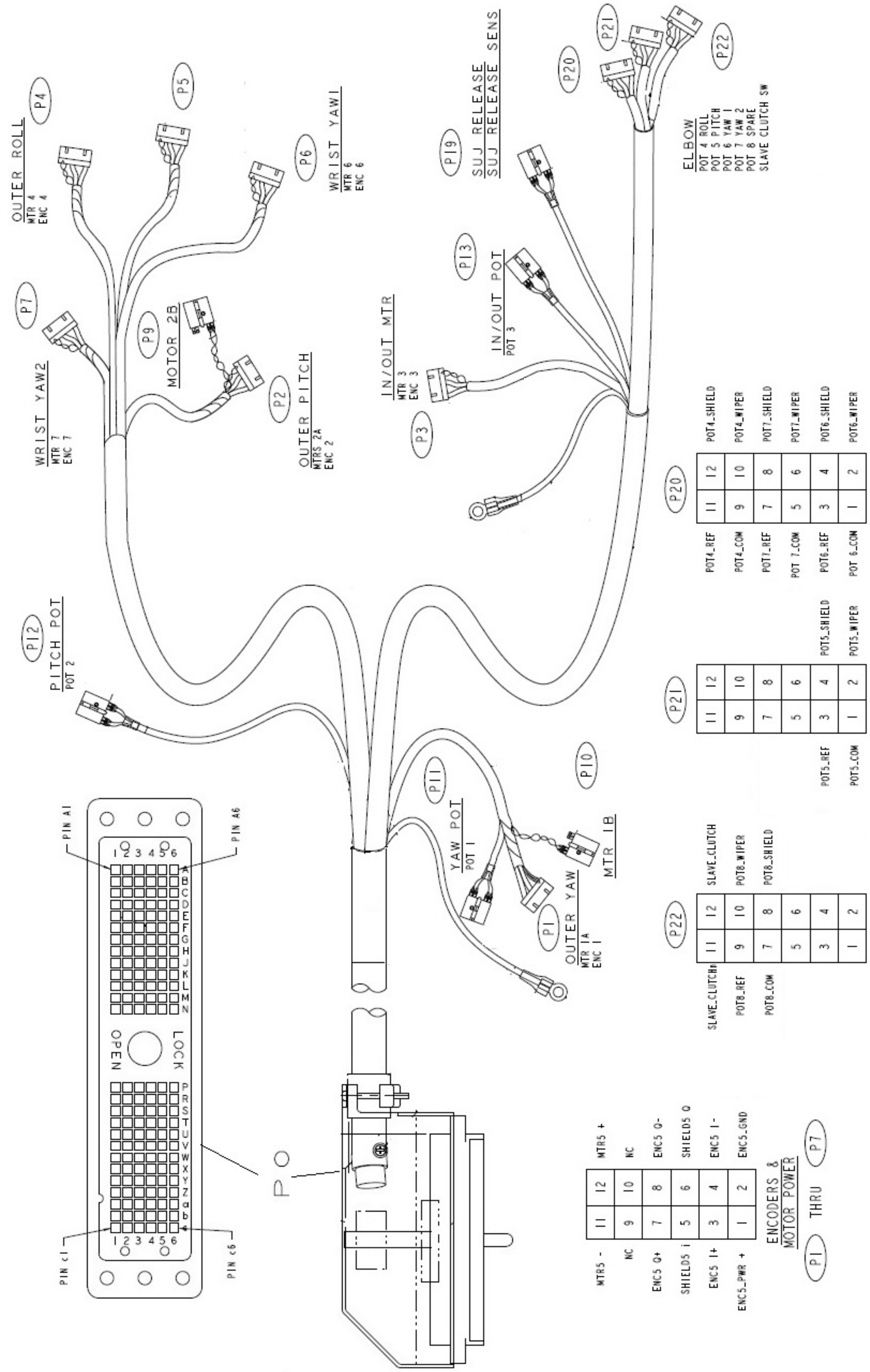
TABLE 8: PSM ACTUATOR OPERATING CONDITIONS

#	Axis	Motor Type	Default Max.		Actual Max. Current		Torque Const	Max. Torque	Gear Ratio*	Encoder
			Voltage (V)	Current (A)	(%)	(Amp)	(Nm/A)	(Nm)		Counts/Rev
1	Outer Yaw	RE025-Twin**	24	1.340	150	2.010	0.043800	0.088	56.50	14400
2	Outer Pitch	RE025-Twin**	24	1.340	150	2.010	0.043800	0.088	56.50	14400
3	In/Out or Insertion	RE025-055-38	24	0.670	150	1.005	0.043800	0.044	336.6	14400
4	Outer Roll	RE025-055-38	24	0.670	150	1.005	0.043800	0.044	11.71	4000
5	Wrist Pitch	RE025-055-38	24	0.670	150	1.005	0.043800	0.044	11.71	4000
6	Wrist Yaw1	RE025-055-38	24	0.670	150	1.005	0.043800	0.044	11.71	4000
7	Wrist Yaw2	RE025-055-38	24	0.670	150	1.005	0.043800	0.044	11.71	4000

* Gear Ratio – the gain from the motor shaft to the actual joint

** RE025-Twin: It represents 2 RE025-055-38 in parallel configuration

The interface to all the electronics and electrical components in the PSM is through a single Zero Insertion Force DL156 pin connector from ITT Canon. Figure 11 shows the layout of the wiring of the connector. P0 is the main interface connector and P1 to P22 are connectors that go to different components of the PSM. The pinouts for the P0 interface connector are available in **APPENDIX B.**



P20				
POT4_REF	11	12	POT4_SHIELD
POT4_COM	9	10	POT4_WIPER
POT7_REF	7	8	POT7_SHIELD
POT 7_COM	5	6	POT7_WIPER
POT6_REF	3	4	POT6_SHIELD
POT 6_COM	1	2	POT6_WIPER

P21			
	11	12	
	9	10	
	7	8	
	5	6	
POT5_REF	3	4	POT5_SHIELD
POT5_COM	1	2	POT5_WIPER

P22			
SLAVE_CLUTCHB	11	12	SLAVE_CLUTCH
POT8_REF	9	10	POT8_WIPER
POT8_COM	7	8	POT8_SHIELD
	5	6	
	3	4	
	1	2	

ENCODERS & MOTOR POWER P1 THRU P7			
MTR5 -	11	12	MTR5 +
NC	9	10	NC
ENC5 Q+	7	8	ENC5 Q-
SHIELD5 i	5	6	SHIELD5 Q
ENC5 I+	3	4	ENC5 I-
ENC5_PWR +	1	2	ENC5_GND

FIGURE 11: PSM INTERFACE CONNECTOR WIRING LAYOUT.

PSM calibration

The calibration files contain values for several physical parameters of the PSM; these are required to transform from raw sensor data to joint space or configuration space. This section describes these parameters and how to use them.

Below is **an example** of a section of the calibration file to elaborate on the relevant parameters (please see the calibration files that came with your Research Kit for the numbers specifically for your hardware).

```
///////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
serial_number:
19798
joint_range_upper_limit:
1.5994 0.94249 0.24001 3.0485 3.0528 3.0376 3.0399
joint_range_lower_limit:
-1.605 -0.93556 -0.002444 -3.0456 -3.0414 -3.0481 -3.0498
pot_input_gain:
-0.00084669 -0.00056092 6.5361e-005 -0.0015207 -0.0015111 -0.0015072 -0.0015292
pot_input_offset:
1.7135 1.1633 -0.018724 3.1464 3.0604 3.0952 3.0948
pot_lower_limit:
144 387 3959 59 38 65 39
pot_upper_limit:
3919 3725 251 4055 4037 4059 4016
///////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
```

The above rows have seven columns corresponding to the seven joints separated by spaces:

- **joint_range_lower_limit** and **joint_range_upper_limit** are the physical joint limits represented in radians as per the DH convention.
- **pot_input_gain** is the gain to transform from the potentiometer ADC value to the joint angle in radians.
- **pot_input_offset** is the offset measured in radians to map the angle measured from the potentiometer to the joint angle as per DH convention.
- **pot_lower_limit** and **pot_upper_limit** are 12 bit ADC values of the joint limits obtained by measuring the voltage across the wiper and ground terminal of the corresponding potentiometer (value of 0 represents 0V and 4096 represents full reference voltage typically 5V).

Therefore, the actual joint angle can be calculated using the following formula**.**

$$\boldsymbol{Joint\ angle = pot\_input\_gain * pot\_adc\_value\ + pot\_input\_offset}$$

Endoscopic Camera Manipulator

Each patient side cart for the full da Vinci standard system contains one Endoscopic Camera Manipulator (ECM), to which the camera/endoscope assembly is attached. The ECM is a slave that is teleoperated by the MTMs when the camera foot-pedal is pressed by the user at the surgeon console. The ECM is not provided as part of the research kit, but this documentation can be used by research groups who are using the dVRK controllers with a full da Vinci standard system. ECM is a 4-DOF actuated manipulator, with joint sensors and actuators for control purposes.

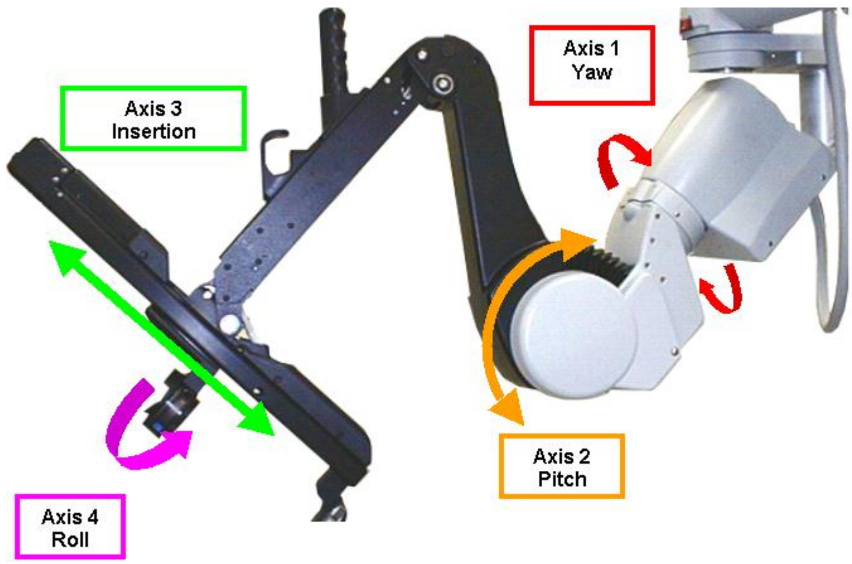


FIGURE 12: JOINTS OF THE ECM AND THEIR DIRECTION OF MOTION

The ECM contains 4 joints. The directions of motion of the 4 joints are illustrated in Figure 12. For the ECM, the joints are qualitatively the same as the first 4 joints of the PSM.

TABLE 9: SUMMARY OF THE ECM JOINTS

ECM Joint	Joint type*	Joint Name	Description
1	1	Outer Yaw	This is the only joint that moves the entire ECM with respect to its mounting base. It pivots the endoscope in a yaw motion about the remote center. Home position (zero joint-angle) is center range of motion, which makes the insertion axis perpendicular to the ECM mounting plate.
2	1	Outer Pitch	This joint pivots the endoscope in a pitching motion about the remote center. Home position (zero joint-angle) is chosen to make the insertion axis perpendicular to the ECM mounting plate, which it turns out is not quite center range of motion.
3	2	In/Out or Insertion	This axis moves the endoscope along the axis of its shaft into or out of the patient. Home position (zero joint angle) is fully retracted, with the instrument's control point located at the remote center.

ECM Joint	Joint type*	Joint Name	Description
4	1	Outer Roll	This axis rolls the endoscope shaft. Home position (zero joint-angle) is center range of motion.

* 0 – No joint
1 – Revolute joint
2 – Prismatic joint

ECM kinematics

This section describes the kinematics of the ECM using the Denavit–Hartenberg (DH) convention or representation. Table 10 lists the DH parameters from the origin of ECM to the tip of ECM (assuming a POC zero degree stereo endoscope).

TABLE 10: DH PARAMETER TABLE FOR ECM

Frame	Joint Name	Joint type	a	α	D	θ
1	Outer Yaw	1	0	$\frac{\pi}{2}$	0	$\frac{\pi}{2}$
2	Outer Pitch	1	0	$-\frac{\pi}{2}$	0	$-\frac{\pi}{2}$
3	In/out or Insertion	2	0	$\frac{\pi}{2}$	$-len_{RCC}$	0
4	Outer Roll	1	0	0	$ScopeLen$	0

The values for the geometric parameters of the PSM mentioned in Table 10 are:

$$len_{RCC} = 0.3822m$$
$$ScopeLen = 0.3829\ m$$

ECM hardware

The ECM has actuators, encoders and sensors for each manipulator joint for providing feedback and actuation. Table 11 summarizes the components of each joint.

TABLE 11: SUMMARY OF THE KEY HARDWARE COMPONENTS IN EACH SECTION OF ECM

Joints	Actuator	Encoder	Potentiometer	Differential line driver Board	Clutch switch
Outer Yaw	Maxon DC motor RE035-071-39	Maxon tacho ENC HEDS 5500 1000IMP 2K on motor	5 K rotary linear POT	RS 422 IC AM26C31	

Joints	Actuator	Encoder	Potentiometer	Differential line driver Board	Clutch switch
Outer Pitch	Maxon DC motor RE035-071-39	Maxon tacho ENC HEDS 5500 1000IMP 2K on motor	5 K rotary linear POT	RS 422 IC AM26C31	
In/out or Insertion	Maxon DC motor RE-025-055-38	ME 16 optical, 160 CPR	5 K rotary linear POT	RS 422 IC AM26C31	
Outer Roll	Maxon DC motor RE-013-032-06	16 counts DME* on motor	5 K rotary linear POT	RS 422 IC AM26C31	

The potentiometers present in each joint are used as additional feedback for the motors of each joint, as well as for an absolute measure of the joint angle. It is important to note that the encoder and potentiometer are linked to the drivetrain differently. The encoders are mounted to the motor shaft, whereas the potentiometers are either cable or gear driven at the joint output side.

TABLE 12: ECM ACTUATOR OPERATING CONDITIONS

#	Axis	Motor Type	Default Max.		Motor resistance	Actual Max. Current		Torque Const	Max. Torque	Gear Ratio*	Encoder
			Voltage (V)	Current (A)	R (ohm)	(%)	(Amp)	(Nm/A)	(Nm)		Counts /Rev
1	Outer Yaw	RE035-071-39	48	0.943	11.5	150	1.4145	0.1190	0.112	240	4000
2	Outer Pitch	RE035-071-39	48	0.943	11.5	150	1.4145	0.1190	0.112	240	4000
3	In/Out or Insertion	RE025-055-38	24	0.670	7.55	150	1.005	0.043800	0.044	2748.55	640
4	Outer Roll	RE-013-032-06	9	0.590	3.5	150	0.885	0.00495	0.00292	300.15	64

* Gear Ratio – the gain from the motor shaft to the actual joint

The interface to all the electronics and electrical components in the ECM is through a single Zero Insertion Force DL156 pin connector from ITT Canon. Figure 14 shows the layout of the wiring of the connector. The pinouts for the P0 interface connector is available in **APPENDIX B.**

The camera arm also contains three brakes on axes 1, 2 and 3. Each brake has specific parameters that should be adjusted in the dVRK software before getting the ECM to work. These parameters include:

- Brake release current (high current): the amount of current required to initially release the brakes
- Brake released current (medium current): the amount of current required to keep the brakes released
- Brake engaged current (low current): the amount of current for engaging the brakes
- Brake release time: the time required for the brake to release

Here are sample parameter values for one particular ECM:

$$brakes.current - high = [0.25, 0.210, 0.60]\ amp$$
$$brakes.current - med = [0.10, 0.10, 0.150]\ amp$$
$$brakes.current - low = [0.0, 0.0, 0.0]\ amp$$
$$brakes\ release\ time = [0.2, 0.2, 0.2]\ s$$

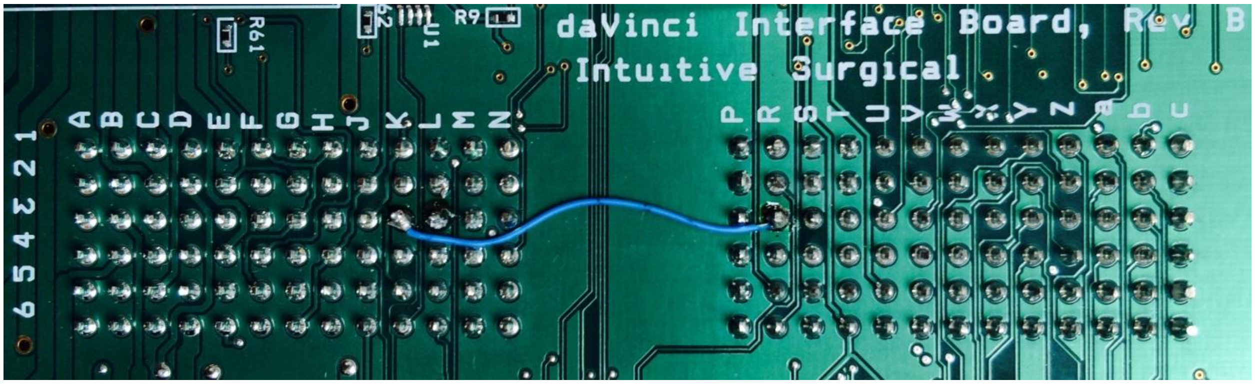
The above parameters will vary from ECM to ECM and require calibration. dVRK ECMs should be adjusted using the procedure explained in sawIntuitiveResearchKit online documentation in GitHub (https://github.com/jhu-dvrk/sawIntuitiveResearchKit/wiki/Full-da-Vinci).

The setup joint switch/button on the ECM does not use the same digital input as the setup joint switch on the PSMs. Unfortunately, this was discovered after the dMIB boards were designed. Hence, users need to modify their ECM dMIB boards by bridging two pairs of pins.

The required modifications are as follows:

- Wire (short) pin K3 to R3
- Wire pin N3 to back of spare digital input on the side of the board (see Figure 13).

Please note that some dMIB boards have the letter labels (A, B, C, E, ...) off by one. Make sure you rely on the following photos to identify the proper pins.



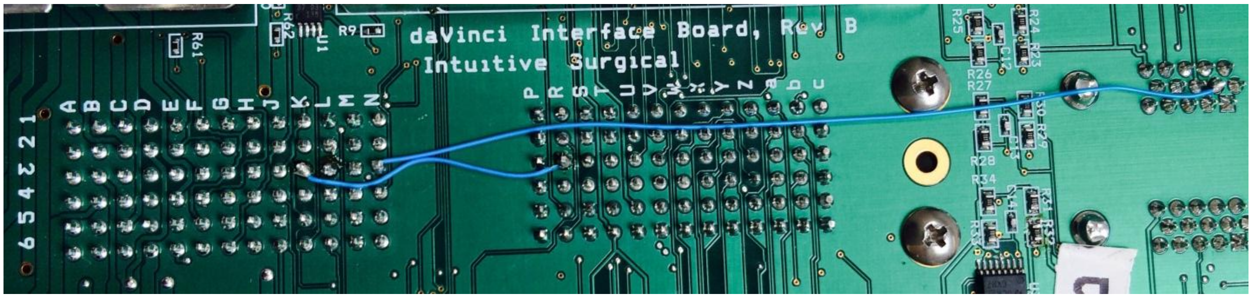


FIGURE 13: DMIB MODIFICATIONS

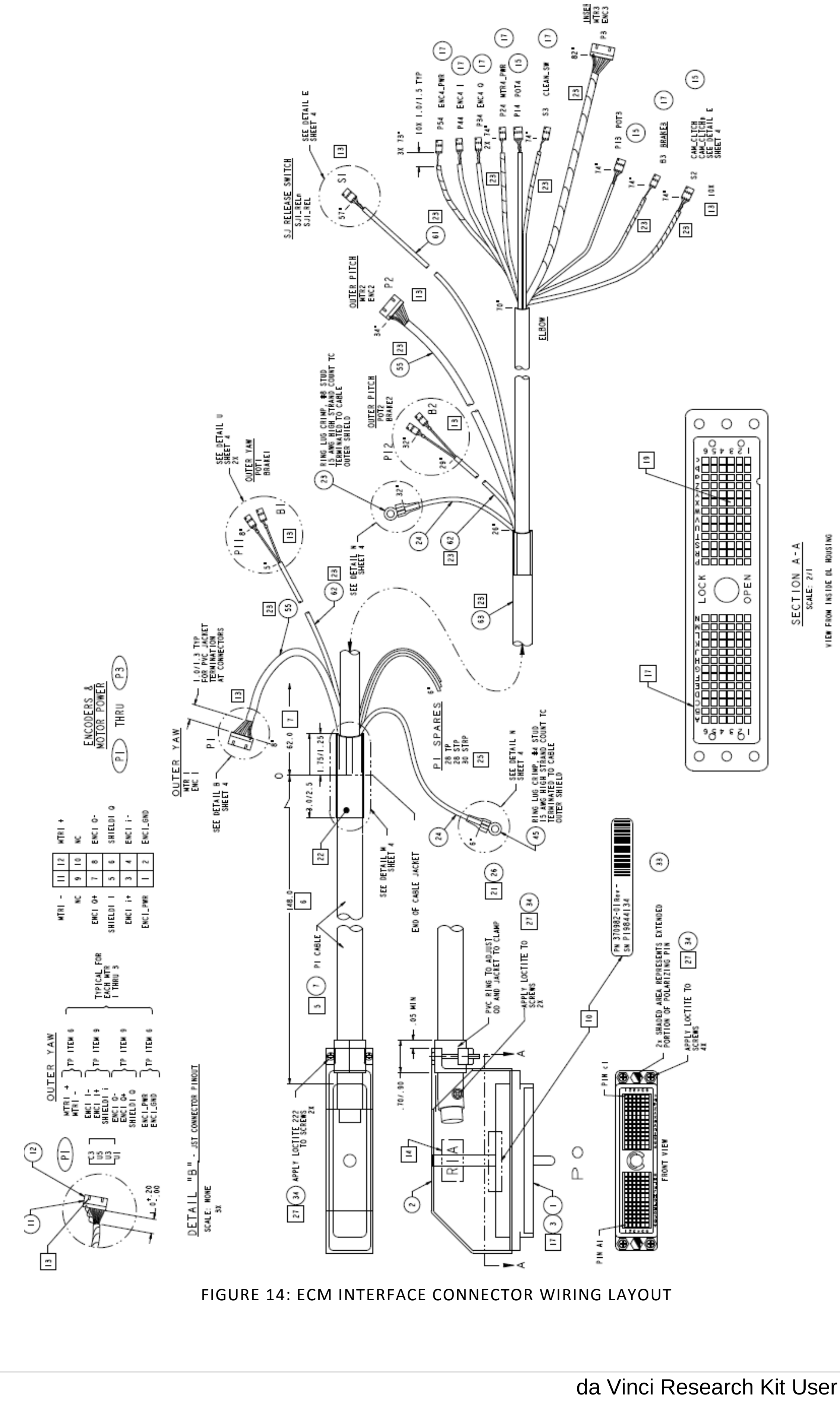


FIGURE 14: ECM INTERFACE CONNECTOR WIRING LAYOUT

ECM calibration

The calibration files contain values for several physical parameters of the ECM; these are required to transform from raw sensor data to joint space or configuration space. This section describes these parameters and how to use them.

Below is **an example** of a section of the calibration file to elaborate on the relevant parameters. Please contact ISI in order to obtain the calibration file for you ECM arms.

```
/////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
serial_number:
21141
joint_range_upper_limit:
1.581733 1.157657 0.254193 1.566741
joint_range_lower_limit:
-1.595183 -0.783710 -0.006022 -1.552676
pot_input_gain:
0.001143 0.000738 -0.000148 -0.000862
pot_input_offset:
-2.360918 -1.340933 0.433055 1.801511
pot_lower_limit:
118.0 232.0 867.0 0.0
pot_upper_limit:
4013.0 3910.0 3307.0 4096.0
/////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
```

The above rows have seven columns corresponding to the seven joints separated by spaces:

- **joint_range_lower_limit** and **joint_range_upper_limit** are the physical joint limits represented in radians as per the DH convention.
- **pot_input_gain** is the gain to transform from the potentiometer ADC value to the joint angle in radians.
- **pot_input_offset** is the offset measured in radians to map the angle measured from the potentiometer to the joint angle as per DH convention.
- **pot_lower_limit** and **pot_upper_limit** are 12 bit ADC values of the joint limits obtained by measuring the voltage across the wiper and ground terminal of the corresponding potentiometer (value of 0 represents 0V and 4096 represents full reference voltage typically 5V).

Therefore, the actual joint angle can be calculated using the following formula.

$$\boldsymbol{Joint\ angle = pot\_input\_gain * pot\_adc\_value\ + pot\_input\_offset}$$

Foot Pedal Tray

Foot pedal tray is a panel of switches, accessed using the foot. On the da Vinci system, they provide additional inputs, such as for initiating the control of camera motion, clutching and swapping the control of three arms/instruments between to MTMs. The foot pedal tray has five pedals and the following describes their typical function in da Vinci system:

- Clutch: This activates the clutch for the MTMs. When pressed the movements of MTMs are not reflected on the PSMs or the ECM. This clutching mode is used to reposition the MTMs, when needed. A quick tap of this switch performs an arm swap, as described above.
- Camera: This activates the camera pose control. When pressed the MTMs control the pose of the camera.
- Focus: This activates the focus control for the camera. The switch has three states: idle, plus and minus.
- 3rd pedal: This typically unused. But in some systems it is used to energize bi-polar cautery instruments.
- COAG: This activates the energy source to a mono-polar cautery instrument.

The functions described above are typical in a full da Vinci system; however, you may choose to map them any way you please in your custom da Vinci implementation!
Figure 15 is a picture of the foot pedal tray.

FIGURE 15: FOOT PEDAL TRAY.

Foot Pedal Tray hardware

Pedals on the foot tray are simple two-terminal switches. The Camera focus pedal has two trip switches, one for 'focus forward' and the other for 'focus reverse'; they are represented by a two-terminal switch. Figure 16 shows the interfacing cable and the pinouts.

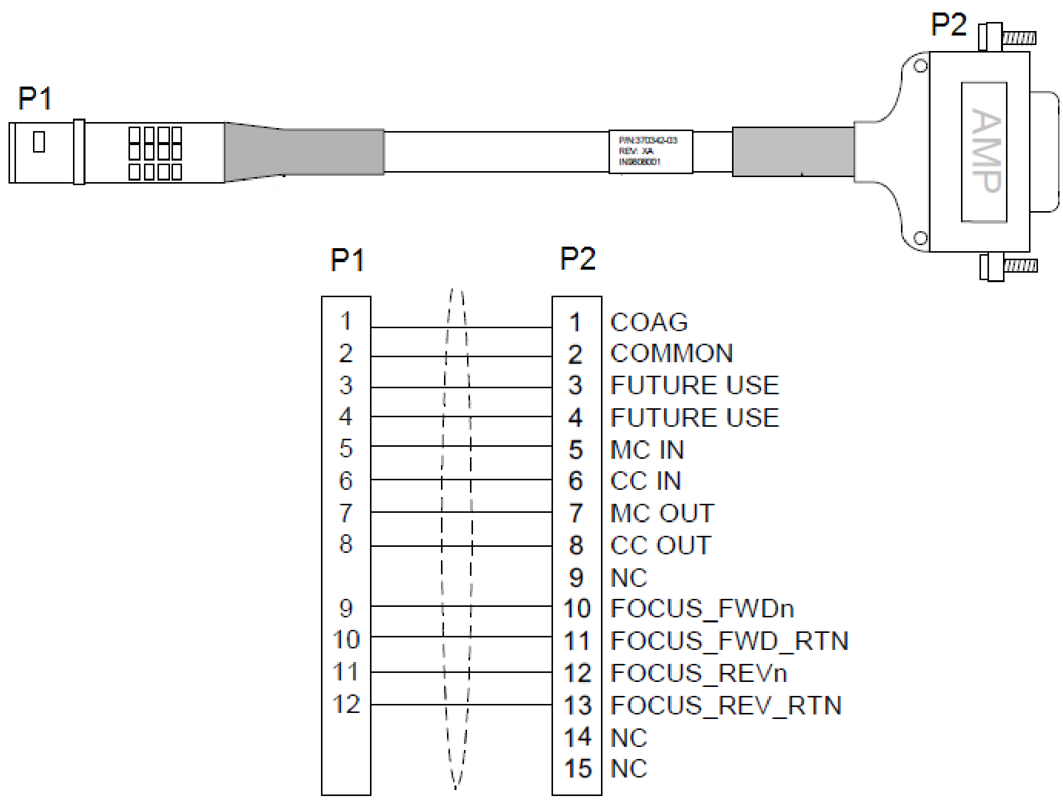


FIGURE 16: FOOT PEDAL TRAY INTERFACE CONNECTOR PINOUTS

KEY:

PIN ABBREVIATION	NAME	DESCRIPTION
COAG	COAG	+ terminal of COAG switch, shorts with - terminal when pressed
COMMON	Common	-terminal of COAG switch
MC IN	Master clutch in	+ terminal of CLUTCH switch, shorts with - terminal when pressed
MC OUT	Master clutch out	- terminal of CLUTCH switch
CC IN	Camera control in	+ terminal of CAMERA switch, shorts with - terminal when pressed
CC OUT	Camera Control out	- terminal of CAMERA switch
FOCUS_FWDn	Focus forward normally open	+ terminal of 'FOCUS +' switch, shorts with - terminal when pressed
FOCUS_FWD_RTN	Focus forward return	- terminal of 'FOCUS +' switch
FOCUS_REVn	Focus reverse normally open	+ terminal of 'FOCUS -' switch, shorts with - terminal when pressed
FOCUS_REV_RTN	Focus reverse return	- terminal of 'FOCUS -' switch

High Resolution Stereo Viewer

The High Resolution Stereo Viewer (HRSV) is the 3D display for the surgeon. It is part of the Surgeon Console. The HRSV displays the output from the stereo camera present on the endoscope. Through the eye piece the surgeon can see a clear, magnified and 3-dimensional view of the surgical field. The HRSV is shown in
Figure 17.

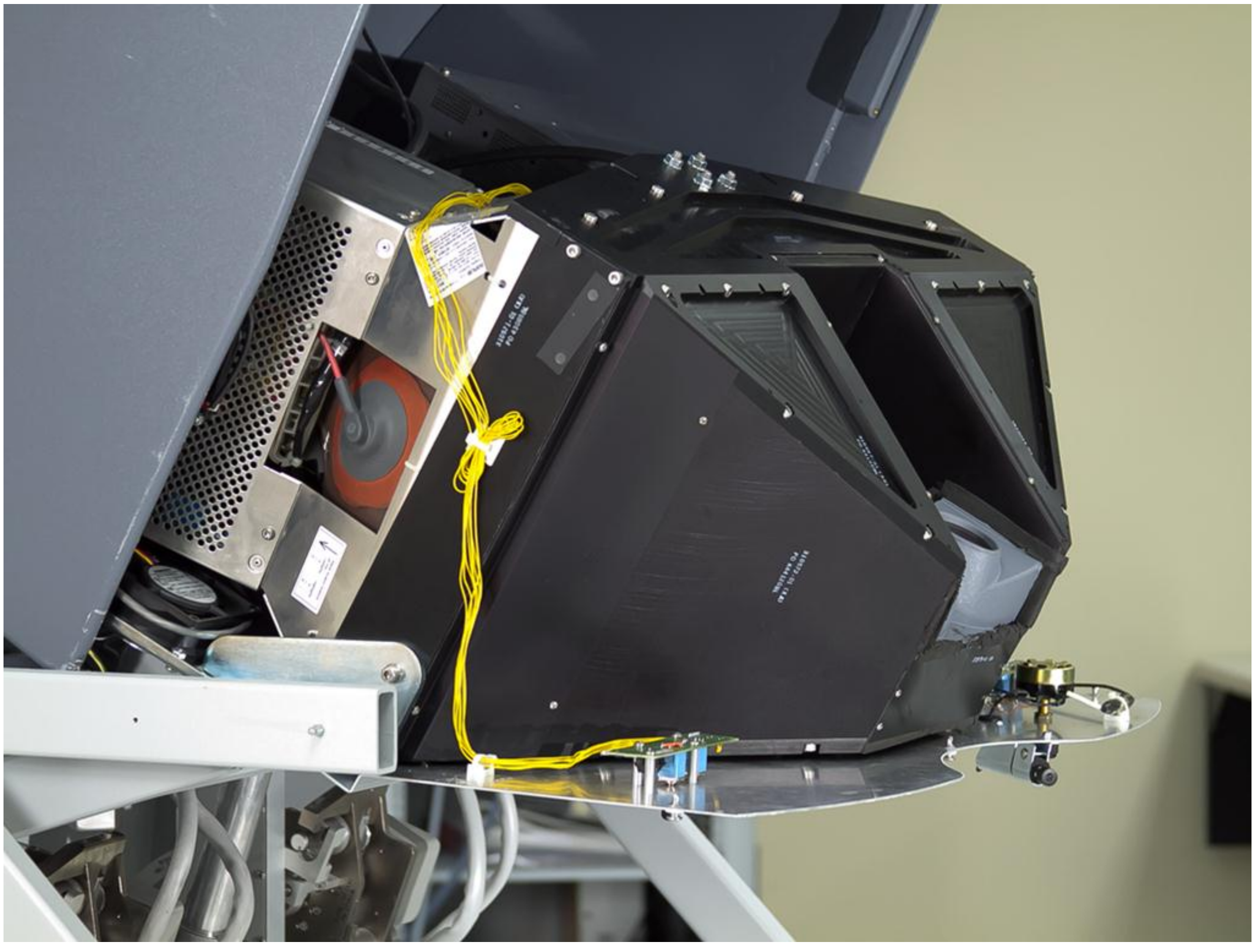


FIGURE 17: HIGH RESOLUTION STEREO VIEWER.

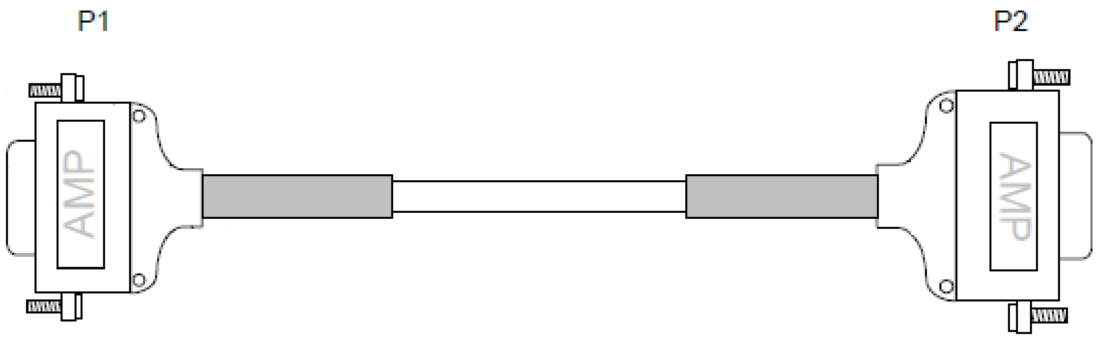
HRSV hardware

The HRSV is a subsystem of the Surgeon Console. The kit is provided with the following hardware.

Eyepiece: It is a simple system of lenses and mirrors that direct the light from the display towards the viewer. They ensure that the output from the display is of the right scale and depth when viewed through it.

CRT display: The HRSV has two Barco MCD214 CRT displays – one for each eye. The CRTs have knobs or potentiometers to control the contrast and brightness. The CRT will be provided with cable that uses a standard VGA input that interfaces with the monitor. Figure 18 shows the wiring and pin layouts for the HRSV.

Table 13 provides the specifications for both the monitors

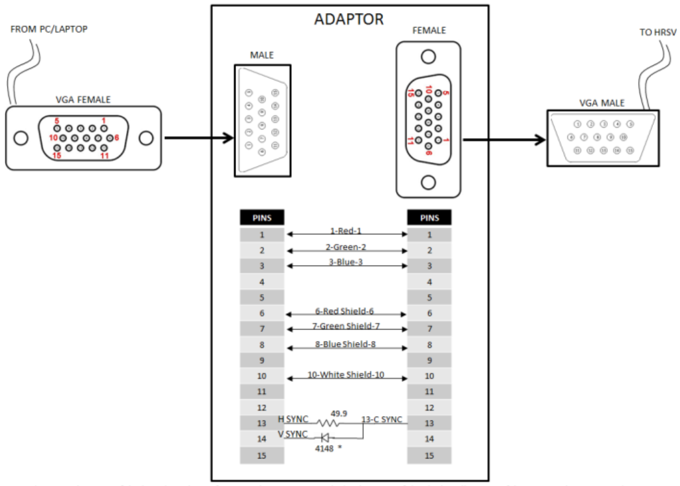


	VGA TO BARCO	
FROM	SIGNAL/COLOR	TO
P1-1	RED	P2-15
P1-6	RED-SHIELD	P2-8
P1-2	GREEN	P2-14
P1-7	GREEN-SHIELD	P2-7
P1-3	BLUE	P2-13
P1-8	BLUE-SHIELD	P2-6
P1-13	WHITE	P2-12
P1-10	WHITE-SHIELD	P2-5

FIGURE 18: VGA TO BARCO CONNECTOR PINOUT.

Adapter for HRSV

The HRSV works on composite Sync signal. Most current VGA signals include a dedicated Vertical Sync (V-Sync) and Horizontal (H-Sync) signal. To make the HRSV work with Desktop or Laptop the adapter shown in Figure 19 is needed to convert the H-Sync and V-Sync signals to a Composite Sync (C-Sync) signal.



*Current direction of diode is the solution for Active low V-Sync signal. The direction of the diode will reverse if driving signal is Active High.

FIGURE 19: HRSV LAPTOP ADAPTER

TABLE 13: HRSV SPECIFICATIONS

Resolution	Refresh Rate	Color Depth
640X480	59.94Hz	16 bit

Mounting Dimensions and Considerations

This section describes the constraints and considerations on how to mount the various components of the kit and how to position them relative to one another on your custom frame.

MTM mounting

The MTMs weigh approximately 34 pounds each, including the cable and each is mounted using an angle bracket at the base of MTM. The angle bracket has four holes placed in a rectangular pattern.
Figure 20 shows the mounting holes and their spacing.

Mounting hole diameter = 0.28 inch

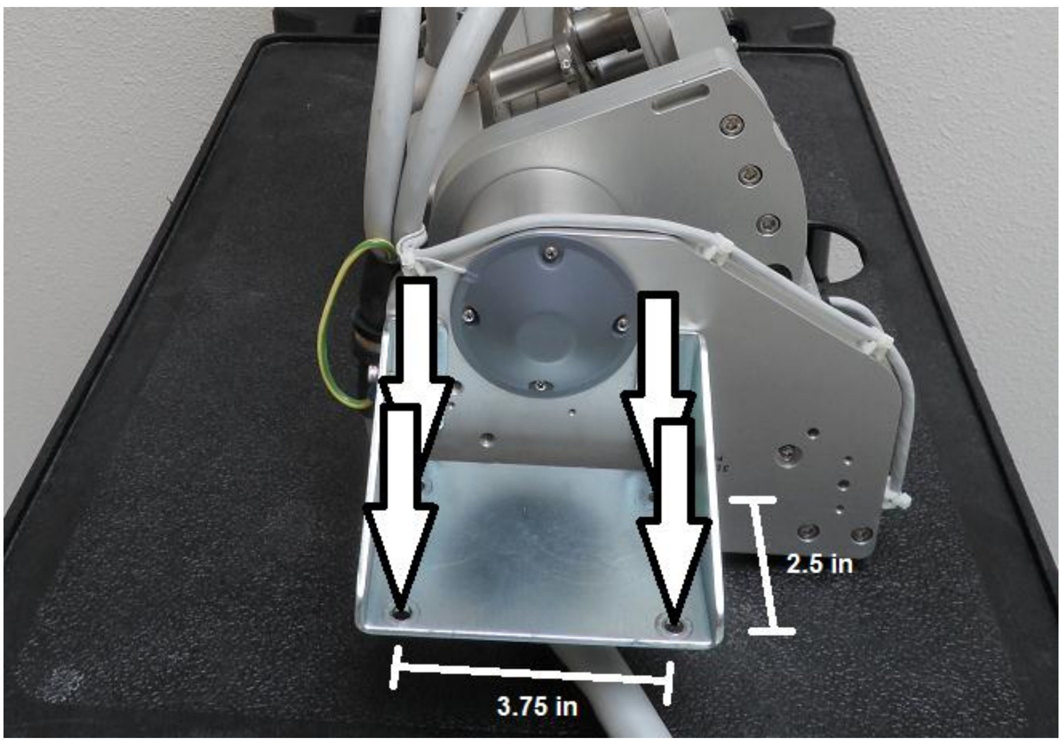


FIGURE 20: MTM TOP VIEW - ANGLE BRACKET AND MOUNTING HOLES.

Two MTMs are provided, the left and the right MTM. In a typical da Vinci system the relative position between them is fixed.
Figure 21 shows the dimensions of the placement of the MTM with respect to the HRSV, the floor and each other.

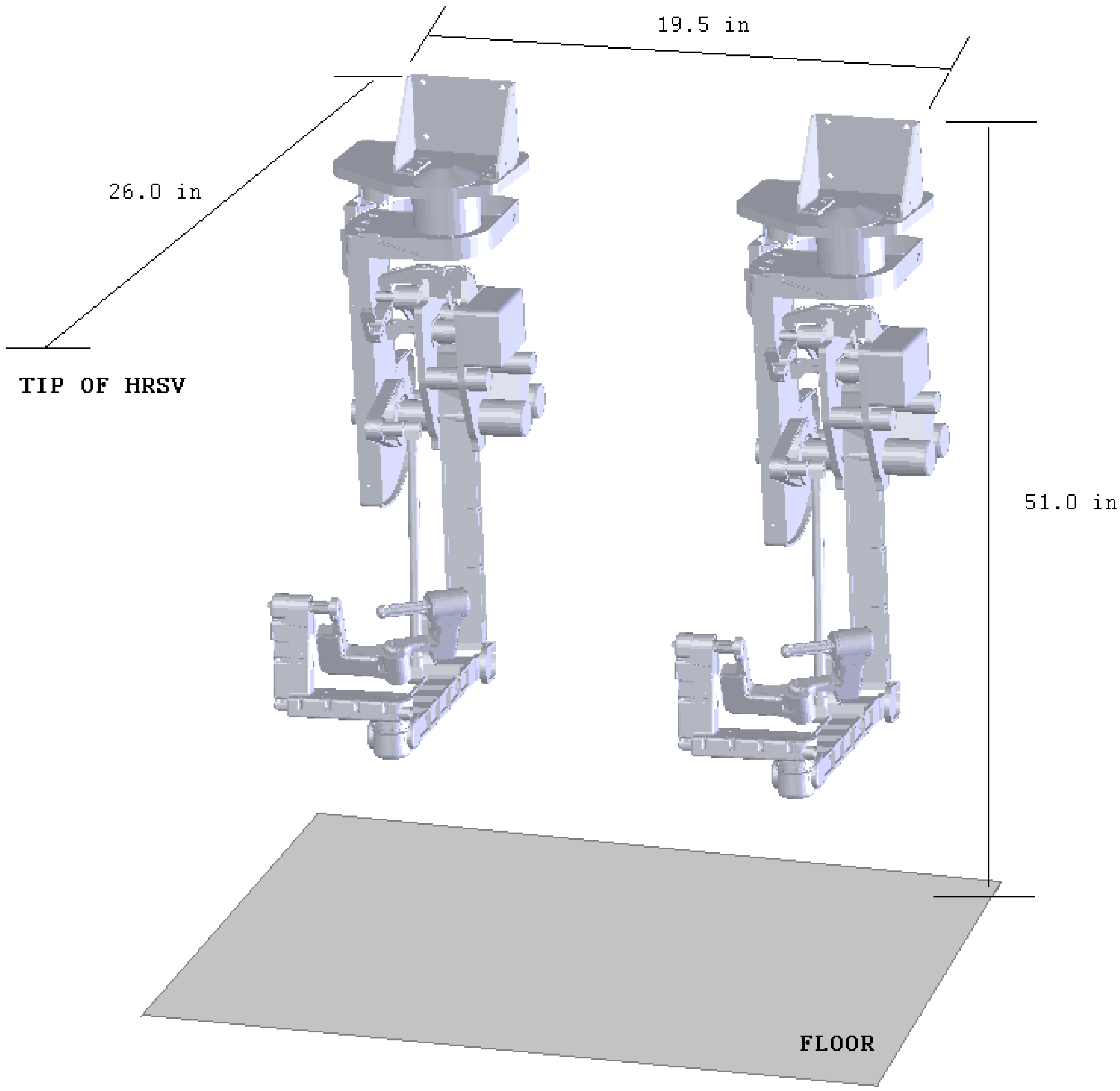


FIGURE 21: RELATIVE POSITIONING OF THE MTMS.

PSM mounting

The PSMs weigh approximately 38 pounds each, including the cable and are mounted using a flat mounting plate or frame. The mounting plate has four holes (0.175 inch diameter) placed in a rectangular pattern.
Figure 22 shows the mounting holes and their spacing.

Mounting hole diameter = 0.175 inch

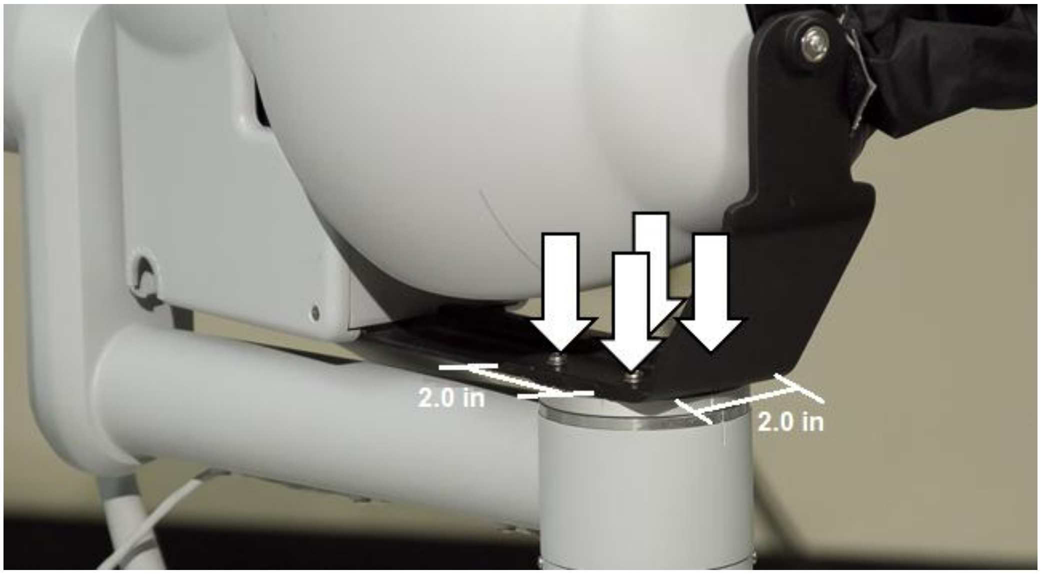


FIGURE 22: PSM SIDE VIEW – MOUNTING PLATE AND MOUNTING HOLES.

Two PSMs are provided. In a typical da Vinci system the relative position between them is not fixed as they are mounted on setup joints, which can be reconfigured to position the PSM as desired.

HRSV mounting

The approximate weight of the HRSV is 115 pounds and is mounted at three locations using a flat mounting surface or frame. Two of the mounting surfaces are located to the sides of the HRSV (left and right), each with two mounting holes (0.2 inch diameter). The third mounting point is located on the top; it has four mounting holes placed in a rectangular pattern.
Figure 23 shows the mounting points.

Side mounting plate: Mounting hole diameter = 0.2 inch

Top mounting plate: Mounting hole diameter = 0.28 inch

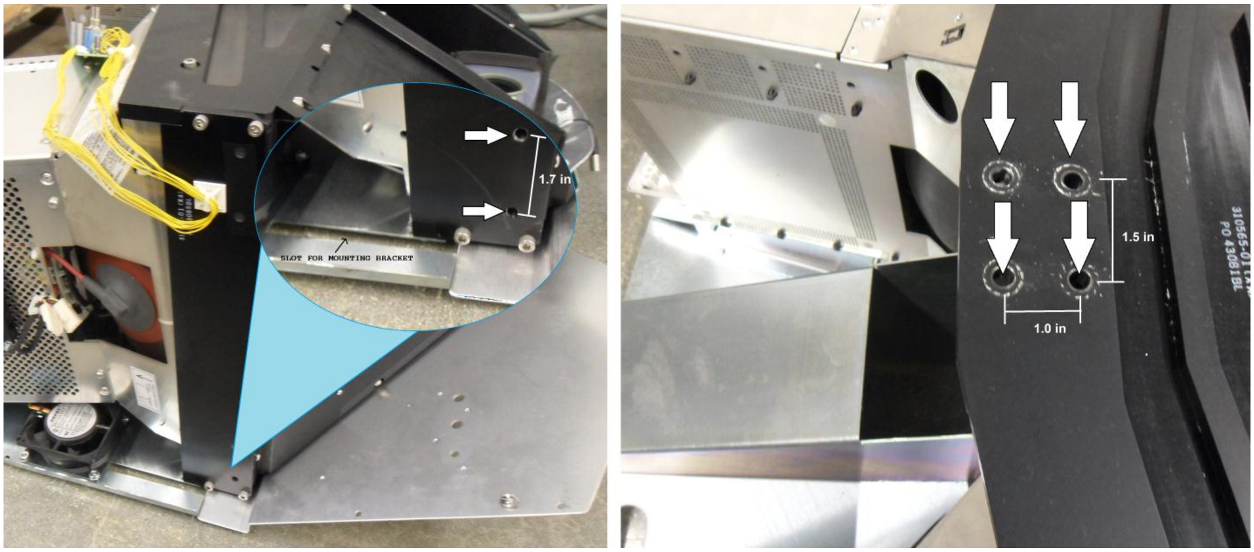


FIGURE 23: HRSV MOUNTING POINTS- LEFT: SIDE MOUNTING HOLES. RIGHT: TOP MOUNTING HOLES.

The HRSV on a typical da Vinci is mounted on an adjustable platform, the height of which can be adjusted to suit the user’s needs.

Mounting Guide for HRSV

The height of the HRSV on the Surgeon Side Console on the da Vinci System is adjustable, based on surgeon preference. Figure 24 describes the mounting dimensions of the HRSV relative to the mounting plate of the MTM’s.

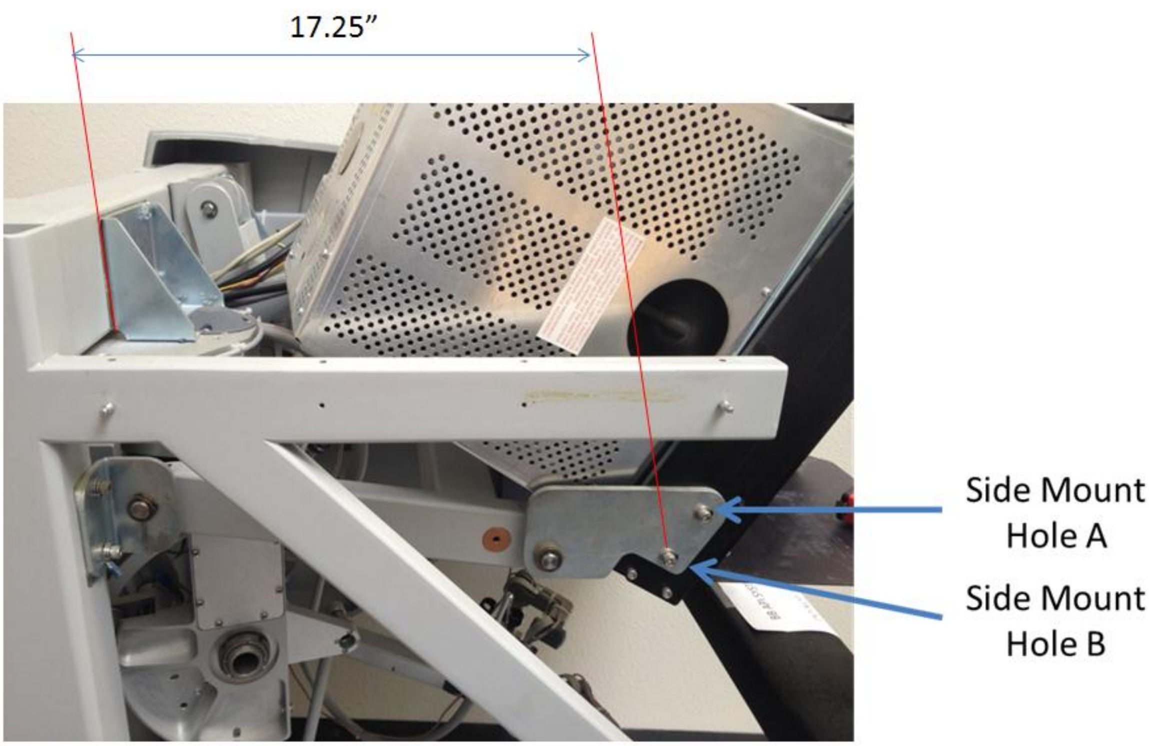
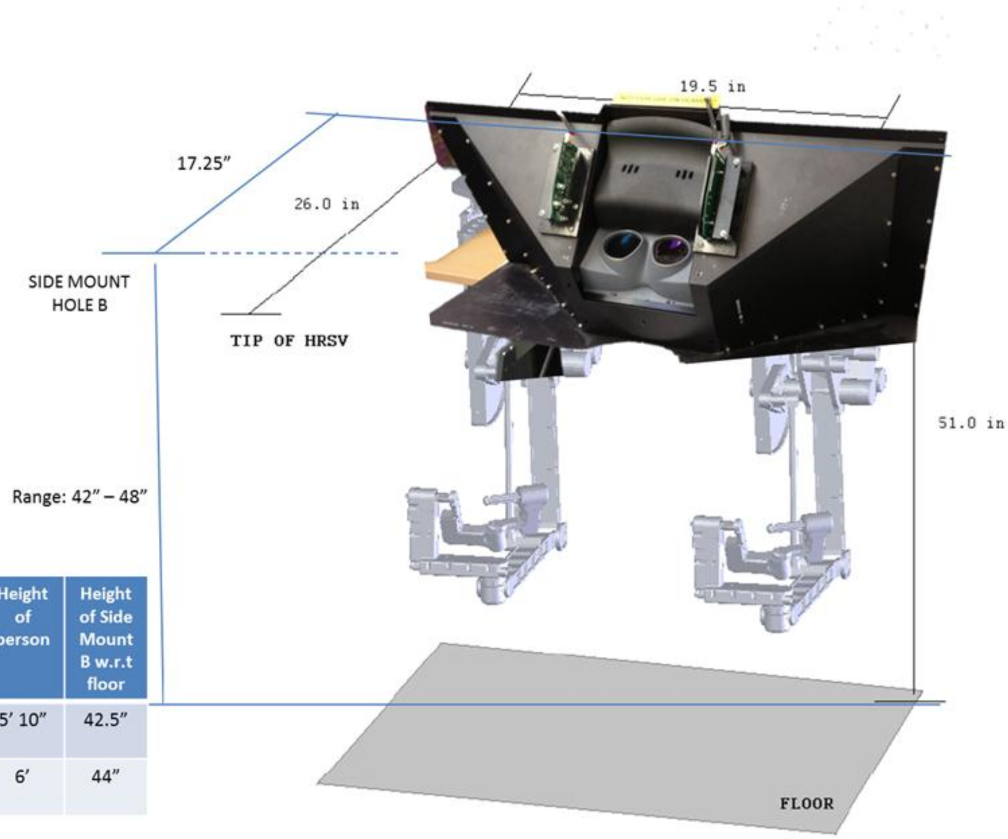


FIGURE 24: DISTANCE OF THE SIDE MOUNTING HOLES FROM MOUNTING PLATE OF MTMS.



Height of person	Height of Side Mount B w.r.t floor
5′ 10″	42.5″
6′	44″

FIGURE 25: RANGE OF HEIGHT OF HRSV.

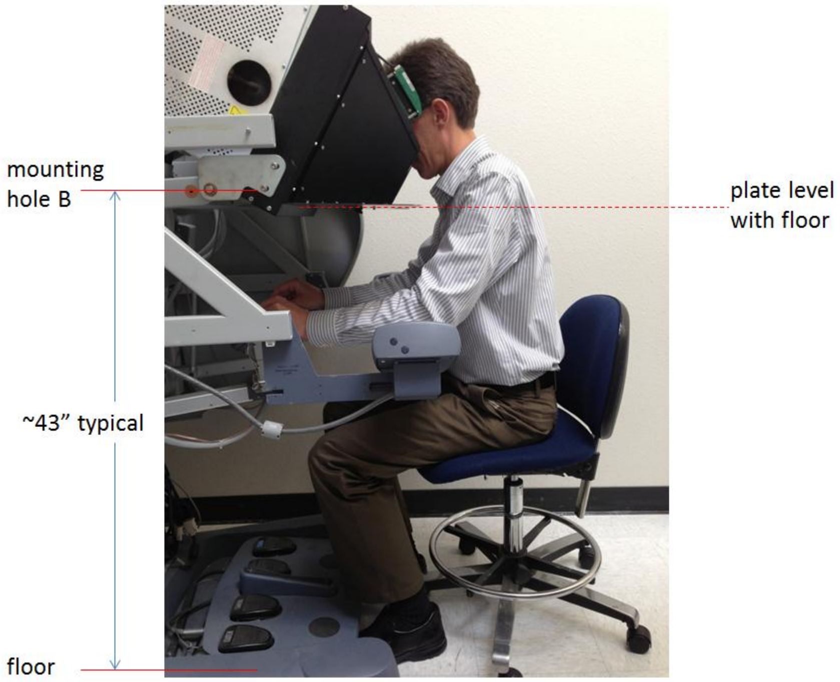


FIGURE 26: SIDE VIEW OF SURGEON SIDE CONSOLE.

Mounting Guide for Accessories

There are four accessories that come with each PSM Arm as shown in Figure 27.

- 8mm Cannula Holder
- 8mm Cannula
- 8mm Cannula Seal
- Sterile Adapter

FIGURE 27: 8MM CANNULA HOLDER, 8MM CANNULA, CANNULA SEAL & STERILE ADAPTER RESPECTIVELY.

8mm Cannula Holder

1. Align the notch on the back of the cannula holder with the corresponding hole on the PSM Arm.
2. Once inside, twist the lock clockwise by 90 degrees to securely lock the cannula holder onto the PSM Arm as shown in Figure 28.

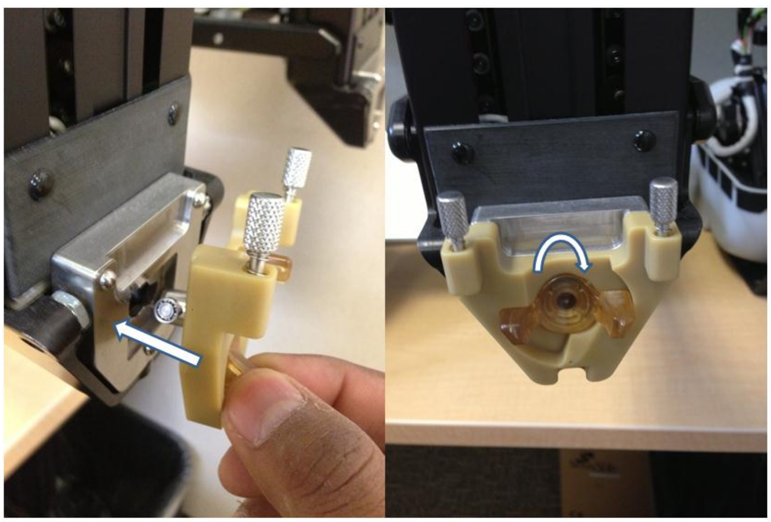


FIGURE 28: INSTALLING CANNULA HOLDER.

8mm Cannula

1. Align the notch present on one side of the cannula towards the cannula holder.
2. Once in place fasten the cannula by the two screws present on the cannula holder as shown in Figure 29. Be careful to avoid cross-threading!

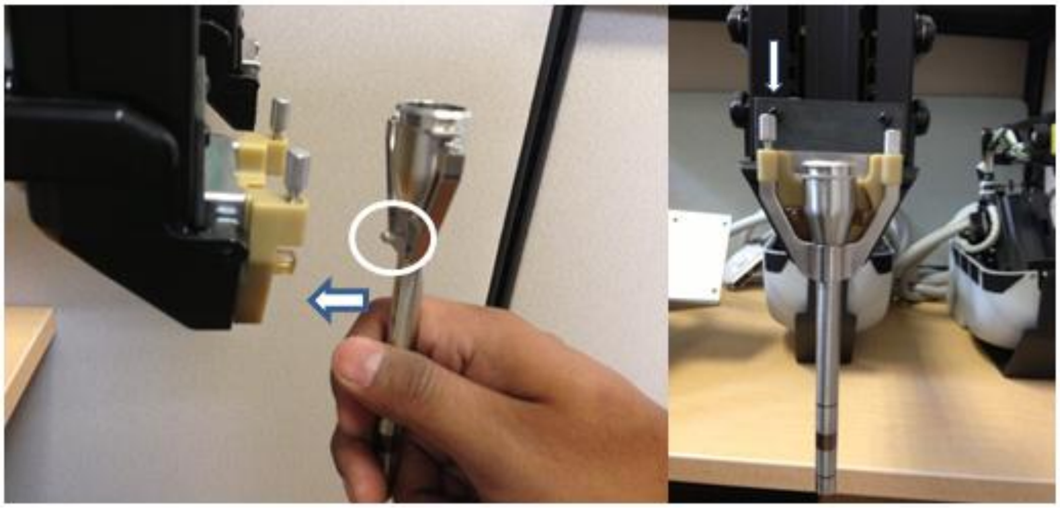


FIGURE 29: INSTALLING THE CANNULA.

Sterile Adapter

1. Notice that the holes on the discs on the sterile adapter and the PSM Arm are not equidistant from the center point as shown in figure below.

FIGURE 30: STERILE ADAPTER MOUNTING.

2. Place the base of the sterile adapter on the mounting rod on the PSM Arm and gently press the top to mount the Sterile Adapter onto the PSM Arm. The latch mechanism will click when engaged.
3. The da Vinci controller rotates all four of the drive axes back and forth in order to engage with the matching features on the disks of the sterile adapter. Your controller should do the same in order to allow the disks to engage properly.

8mm Cannula Seal

1. Fit the Cannula Seal on top of the cannula as shown in Figure 31. This part is not essential, unless you will be working in an insufflated model.

FIGURE 31: 8MM CANNULA SEAL.

Example Mount Setup

The components of the da Vinci Research Kit can be mounted on a custom frame, such as one built using 80/20 extruded aluminum components. An example of an existing implementation of this is shown in
Figure 322, which illustrates a setup at Johns Hopkins University.

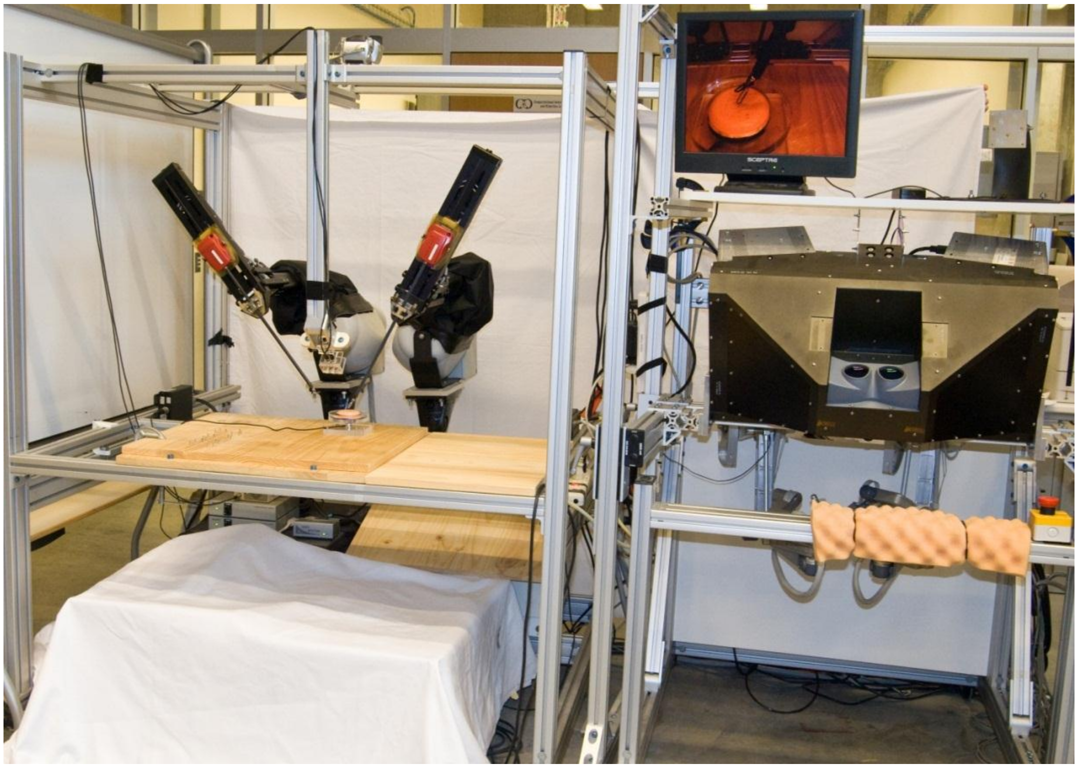


FIGURE 32: EXAMPLE SETUP OF THE DA VINCI KIT

Interfacing and Signals

Interfacing

The interfacing connectors for the HRSV and Foot Panel Tray are standard DB-15 connectors. The PSMs and MTMs use a special 156-pin Zero Insertion Force connector. With your kit, you may have received a set of receptacles that match this 156-pin connector. The 156-pin receptacles are through-hole components and can be mounted on a printed circuit board directly.

Figure 33 and

Figure 34 show the connectors and receptacle available in the kit.

FIGURE 33: DL 156 ZIF CONNECTOR AND RECEPTACLE.

FIGURE 34: DB 15 CONNECTOR.

Signals

The details of the signals and power supply for some of the non-trivial electronic components are discussed below.

Encoders

The encoders are quadrature incremental encoders; they have two channels A and B. The signals from the encoders are fed through a differential line driver as shown in

Figure 35. Channel A has the differential output I+ and I- and Channel B has the differential output Q+ and Q-. The power to the encoders and the differential line driver electronics is supplied through the encoder power wire.

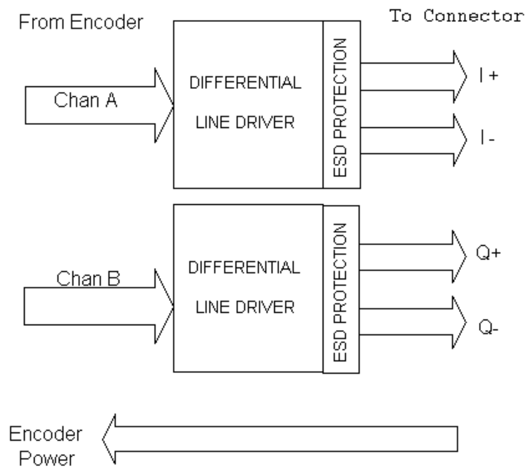


FIGURE 35: SIGNAL FLOW DIAGRAM FOR ENCODERS.

Note: A termination resistance of 120 ohms may be required across i+, i- and Q+, Q-

TABLE 14: ENCODERS PIN FUNCTION AND DESCRIPTION

PINS	TYPE	VALUE	DESCRIPTION
ENCx_PWR	Pwr	5 V	Power
ENCx i+	Output	HIGH or LOW	Digital output of channel A
ENCx i-	Output	HIGH or LOW	Digital output, complement of i+
ENC Q+	Output	HIGH or LOW	Digital output of channel B
ENC Q-	Output	HIGH or LOW	Digital output, complement of Q+
ENC_GND	Gnd	Ground	Ground

Hall Effect Sensors

The Hall Effect sensors used in the MTMs are simple 3-terminal analog sensors as shown in Figure 36. They measure the strength of the magnetic field. In the MTMs the magnetic field is generated by a permanent magnet that is integrated into the finger grip levers.

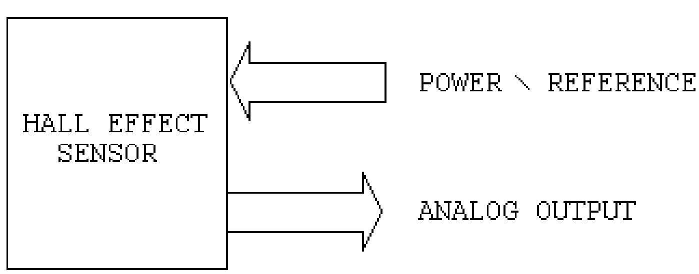


FIGURE 36: SIGNAL FLOW DIAGRAM FOR HALL EFFECT SENSORS.

TABLE 15: HALL EFFECT SENSOR PIN FUNCTION AND DESCRIPTION.

PINS	TYPE	VALUE	DESCRIPTION
HEx REF	Pwr	5V	Reference voltage
HEx OUT	Output	0-5V	Analog output, measuring the magnetic field
HEx GND	Gnd	Ground	Ground

Setup Joints Clutch Switch

The setup joint clutch switch is a 4 terminal switch present on the PSM on the second link of the PSM to float the setup joint of the respective PSM. The switch has both normally closed and normally open terminals and it can be accessed through the PSM 156 pin DL connector.

TABLE 16: SETUP JOINTS CLUTCH SWITCH PIN FUNCTION.

PIN NUMBER	NAME	DESCRIPTION
K4	SJ2_REL	Normally closed shorted to ground. Circuit breaks on press of the switch
L4	SJ2_GNDn	Ground terminal
M4	GND	Ground terminal
N4	SJ2_RELn	Normally Open. Circuit shorts to ground on press of the switch

Slave Clutch Switch

The slave clutch switch is a 2 terminal switch present on the PSM near the instrument mount to float the PSM axis. The switch is normally open passive switch and it can be accessed through the PSM 156 pin DL connector.

TABLE 17: SLAVE CLUTCH SWITCH PIN FUNCTION.

PIN NUMBER	NAME	DESCRIPTION
P3	SLAVE CLUTCHn	The switch is normally open and the two terminal shorts on press
R3	SLAVE CLUTCH SW	

Sterile Adapter Reed Switch

Sterile adapter reed switch is a 2 terminal switch present on the PSM to detect the presence of the sterile adapter. The switch is normally open passive switch and it can be accessed through the PSM 156 pin DL connector. Note that some modification of the sterile adapter may be required to determine presence through this mechanism. Please contact us for further details.

TABLE 18: STERILE ADAPTER REED SWITCH PIN FUNCTION.

PIN NUMBER	NAME	DESCRIPTION
R2	REED SWITCH (ST ADAP)	The switch is normally open and the two terminal shorts on press
S2	GND ST ADAP	

Instrument Loop Back Switch

Instrument loop back switch is a 2 terminal switch present on the PSM to detect the presence of the instrument. The switch is normally open passive switch and it can be accessed through the PSM 156 pin DL connector.

TABLE 19: INSTRUMENT LOOP BACK SWITCH PIN FUNCTION

PIN NUMBER	NAME	DESCRIPTION
S3	INST LOOP BACK	The switch is normally open and the two terminal shorts on press
T3	INST LOOP BACK R	

APPENDIX A

Pinouts for DL 156 ZIF connector for MTM:

WIRE TABLE			
FROM	TO	DESC	COLOR
P0-A1		NC	
A2		NC	
A3		NC	
A4		NC	
A5		NC	
A6		NC	
B1		NC	
B2		NC	
B3	P6-17	MTR6 -	GRAY
B4	P6-18	MTR6 +	RED
B5	P2-11	MTR2 -	GRAY
B6	P2-12	MTR2 +	RED
C1	P4-11	MTR4 -	GRAY
C2	P4-12	MTR4 +	RED
C3	P1-12	MTR1 +	RED
C4	P1-11	MTR1 -	GRAY
C5		NC	
C6		NC	
D1	P7-18	MTR7 +	RED
D2	P7-17	MTR7 -	GRAY
D3		NC	
D4		NC	
D5	P5-18	MTR5 +	RED
D6	P5-17	MTR5 -	GRAY
E3	P3-12	MTR3 +	RED
E4	P3-11	MTR3 -	GRAY
E1	P11-4	POT1 SHLD	SHLD
E2	P11-1	POT1 REF	RED
F1	P11-3	POT1 GND	BLK
F2	P11-2	POT1 WIPER	WHT
F3	P12-4	POT2 SHLD	SHLD
F4	P12-1	POT2 REF	RED
G3	P12-3	POT2 GND	BLK
G4	P12-2	POT2 WIPER	WHT
E5	P13-4	POT3 SHLD	SHLD
E6	P13-1	POT3 REF	RED
F5	P13-3	POT3 GND	BLK
F6	P13-2	POT3 WIPER	WHT
G1	P14-4	POT4 SHLD	SHLD
G2	P14-1	POT4 REF	RED
H1	P14-3	POT4 GND	BLK
H2	P14-2	POT4 WIPER	WHT
H3	P5-10	POT5 SHLD	SHLD
H4	P5-16	POT5 REF	RED
J3	P5-12	POT5 GND	BLK
J4	P5-14	POT5 WIPER	WHT
G5	P6-10	POT6 SHLD	SHLD
G6	P6-16	POT6 REF	RED
H5	P6-12	POT6 GND	BLK
H6	P6-14	POT6 WIPER	WHT
J1	P7-10	POT7 SHLD	SHLD
J2	P7-16	POT7 REF	RED
K1	P7-12	POT7 GND	BLK
K2	P7-14	POT7 WIPER	WHT
J5		NC	
J6		NC	
K5		NC	
K6		NC	

WIRE TABLE			
FROM	TO	DESC	COLOR
P0-L1		NC	
M1			
N1			
L2		NC	
M2		NC	
N2		NC	
K3			
L3			
M3			
N3			
K4		NC	
L4		NC	
M4		NC	
N4		NC	
L5		NC	
M5		NC	
N5			
L6			
M6			
N6			
P1		NC	
R1		NC	
S1		NC	
P2		NC	
R2		NC	
S2		NC	
P3		NC	
R3		NC	
P4		NC	
R4		NC	
S3		NC	
T3		NC	
S4		NC	
T4		NC	
P5	P7-2	HE1 SHLD	SHLD
R5	P7-6	HE1 OUT	WHT
S5	P7-4	HE1 GND	BLK
T5	P7-8	HE1 REF	RED
P6	P6-2	HE2 SHLD	SHLD
R6	P6-6	HE2 OUT	WHT
S6	P6-4	HE2 GND	BLK
P0-T6	P6-8	HE2 REF	RED

WIRE TABLE			
FROM	TO	DESC	COLOR
P0-U1	P1-3	ENC1 I+	RED
U2	P1-4	ENC1 i-	GRAY
T2	P1-5	SHLD1 I	SHLD
T2	P1-6	SHLD1 Q	SHLD
U3	P1-7	ENC1 Q+	RED
U4	P1-8	ENC1 Q-	GRAY
U5	P1-1	ENC1_PWR	RED
U6	P1-2	ENC1_GND	GRAY
V1	P2-3	ENC2 i+	RED
V2	P2-4	ENC2 i-	GRAY
T1	P2-5	SHLD2 I	SHLD
T1	P2-6	SHLD2 Q	SHLD
V3	P2-7	ENC2 Q+	RED
V4	P2-8	ENC2 Q-	GRAY
V5	P2-1	ENC2_PWR	RED
V6	P2-2	ENC2_GND	GRAY
W1	P3-3	ENC3 i+	RED
W2	P3-4	ENC3 I-	GRAY
c6	P3-5	SHLD3 i	SHLD
c6	P3-6	SHLD3 Q	SHLD
W3	P3-7	ENC3 Q+	RED
W4	P3-8	ENC3 Q-	GRAY
W5	P3-1	ENC3_PWR	RED
W6	P3-2	ENC3_GND	GRAY
X1	P4-3	ENC4 i+	RED
X2	P4-4	ENC4 i-	GRAY
c5	P4-5	SHLD4 i	SHLD
c5	P4-6	SHLD4 Q	SHLD
X3	P4-7	ENC4 Q+	RED
X4	P4-8	ENC4 Q-	GRAY
X5	P4-1	ENC4_PWR	RED
X6	P4-2	ENC4_GND	GRAY
Y1	P5-11	ENC5 I+	RED
Y2	P5-13	ENC5 i-	GRAY
c4	P5-15	SHLD5 I	SHLD
c4	P5-9	SHLD5 Q	SHLD
Y3	P5-5	ENC5 Q+	RED
Y4	P5-7	ENC5 Q-	GRAY
Y5	P5-1	ENC5_PWR	RED
Y6	P5-3	ENC5_GND	GRAY
Z1	P6-11	ENC6 i+	RED
Z2	P6-13	ENC6 i-	GRAY
c3	P6-15	SHLD6 I	SHLD
c3	P6-9	SHLD6 Q	SHLD
Z3	P6-5	ENC6 Q+	RED
Z4	P6-7	ENC6 Q-	GRAY
Z5	P6-1	ENC6_PWR	RED
Z6	P6-3	ENC6_GND	GRAY
a1	P7-11	ENC7 i+	RED
a2	P7-13	ENC7 I-	GRAY
c2	P7-15	SHLD7 i	SHLD
c2	P7-9	SHLD7 Q	SHLD
a3	P7-5	ENC7 Q+	RED
a4	P7-7	ENC7 Q-	GRAY
a5	P7-1	ENC7_PWR	RED
a6	P7-3	ENC7_GND	GRAY
b1		NC	
b2		NC	
c1		NC	
c1		NC	
b3		NC	
b4		NC	
b5		NC	
P0-b6		NC	

FIGURE 37: MTM INTERFACE CONNECTOR PINOUTS.

Key:

MTRx +/-	Motor ‘x’ Positive/Negative	Positive/Negative terminal of motor on joint ‘x’
POTx	Potentiometer ‘x’	Potentiometer in the joint ‘x’
ENCx Q/i +/-	Encoder ‘x’ channel Q/i Positive/Negative	Differential signal of the channels from Encoder on joint ‘x’
HEx	Hall Effect Sensor ‘x’	Hall effect sensor on the finger grips ‘x’ = 1 or 2
REF	Reference	Reference voltage
SHLD	Shield	Shielding for signals
PWR	Power	Power supply
GND	Ground	Ground terminal

APPENDIX B

Pinouts for DL 156 ZIF connector for PSM:

WIRE TABLE			
FROM	TO	DESC	COLOR
P0-A1		NC	
A2		NC	
A3		NC	
A4		NC	
A5		NC	
A6		NC	
B1		NC	
B2		NC	
B3	P6-11	MTR6 -	BLK
B4	P6-12	MTR6 +	RED
B5	P2-11	MTR2A -	BLK
B6	P2-12	MTR2A +	RED
C1	P4-11	MTR4 -	BLK
C2	P4-12	MTR4 +	RED
C3	P1-12	MTR1A +	RED
C4	P1-11	MTR1A -	BLK
C5	P9-2	MTR2B -	BLK
C6	P9-1	MTR2B +	RED
D1	P7-12	MTR7 +	RED
D2	P7-11	MTR7 -	BLK
D3	P10-1	MTR1B +	RED
D4	P10-2	MTR1B -	BLK
D5	P5-12	MTR5 +	RED
D6	P5-11	MTR5 -	BLK
E3	P3-12	MTR3 +	RED
E4	P3-11	MTR3 -	BLK
E1	P11-4	POT1 SHLD	SHLD
E2	P11-1	POT1 REF	RED
F1	P11-3	POT1 GND	BLK
F2	P11-2	POT1 WIPER	WHT
F3	P12-4	POT2 SHLD	SHLD
F4	P12-1	POT2 REF	RED
G3	P12-3	POT2 GND	BLK
G4	P12-2	POT2 WIPER	WHT
E5	P13-4	POT3 SHLD	SHLD
E6	P13-1	POT3 REF	RED
F5	P13-3	POT3 GND	BLK
F6	P13-2	POT3 WIPER	WHT
G1	P20-12	POT4 SHLD	SHLD
G2	P20-11	POT4 REF	RED
H1	P20-9	POT4 COM	BLK
H2	P20-10	POT4 WIPER	WHT
H3	P21-4	POT5 SHLD	SHLD
H4	P21-3	POT5 REF	RED
J3	P21-1	POT5 COM	BLK
J4	P21-2	POT5 WIPER	WHT
G5	P20-4	POT6 SHLD	SHLD
G6	P20-3	POT6 REF	RED
H5	P20-1	POT6 COM	BLK
H6	P20-2	POT6 WIPER	WHT
J1	P20-8	POT7 SHLD	SHLD
J2	P20-7	POT7 REF	RED
K1	P20-5	POT7 COM	BLK
K2	P20-6	POT7 WIPER	WHT
J5	P22-8	POT8 SHLD	SHLD
J6	P22-9	POT8 REF	RED
K5	P22-7	POT8 COM	BLK
K6	P22-10	POT8 WIPER	WHT

WIRE TABLE			
FROM	TO	DESC	COLOR
P0-L1		NC	
M1			
N1			
L2		NC	
M2		NC	
N2		NC	
K3		NC	
L3		NC	
M3		NC	
N3		NC	
K4	P19-3	SJ2_REL	RED
L4	P19-4	SJ2_GNDn	BLK
M4	P19-2	GND	BLK
N4	P19-1	SJ2_RELn	RED
L5		NC	
M5		NC	
N5			
L6			
M6			
N6			
P1			
R1			
S1	P21-9	GND	BLK
P2	P21-7	SHLD ST ADAP	SHLD
R2	P21-6	REED SWITCH (ST ADAP)	RED
S2	P21-5	GND ST ADAP	BLK
P3	P22-11	SLAVE CLUTCHn	BLK
R3	P22-12	SLAVE CLUTCH SW	RED
P4		NC	
R4		NC	
S3	P21-11	INST LOOP BACK	RED
T3	P21-12	INST LOOP BACK R	BLK
T4		NC	
P5			
R5			
S5			
T5			
P6			
R6			
S6			
P0-T6			

WIRE TABLE			
FROM	TO	DESC	COLOR
P0-U1	P1-3	MTR1 I+	RED
U2	P1-4	MTR1 i-	BLK
T2	P1-5	SHLD1 i	SHLD
T2	P1-6	SHLD1 Q	SHLD
U3	P1-7	MTR1 Q+	RED
U4	P1-8	MTR1 Q-	BLK
U5	P1-1	ENC1_PWR	RED
U6	P1-2	ENC1_GND	BLK
V1	P2-3	MTR2 I+	RED
V2	P2-4	MTR2 i-	BLK
T1	P2-5	SHLD2 I	SHLD
T1	P2-6	SHLD2 Q	SHLD
V3	P2-7	MTR2 Q+	RED
V4	P2-8	MTR2 Q-	BLK
V5	P2-1	ENC2_PWR	RED
V6	P2-2	ENC2_GND	BLK
W1	P3-3	MTR3 i+	RED
W2	P3-4	MTR3 i-	BLK
c6	P3-5	SHLD3 i	SHLD
c6	P3-6	SHLD3 Q	SHLD
W3	P3-7	MTR3 Q+	RED
W4	P3-8	MTR3 Q-	BLK
W5	P3-1	ENC3_PWR	RED
W6	P3-2	ENC3_GND	BLK
X1	P4-3	MTR4 i+	RED
X2	P4-4	MTR4 I-	BLK
c5	P4-5	SHLD4 i	SHLD
c5	P4-6	SHLD4 Q	SHLD
X3	P4-7	MTR4 Q+	RED
X4	P4-8	MTR4 Q-	BLK
X5	P4-1	ENC4_PWR	RED
X6	P4-2	ENC4_GND	BLK
Y1	P5-3	MTR5 i+	RED
Y2	P5-4	MTR5 i-	BLK
c4	P5-5	SHLD5 i	SHLD
c4	P5-6	SHLD5 Q	SHLD
Y3	P5-7	MTR5 Q+	RED
Y4	P5-8	MTR5 Q-	BLK
Y5	P5-1	ENC5_PWR	RED
Y6	P5-2	ENC5_GND	BLK
Z1	P6-3	MTR6 I+	RED
Z2	P6-4	MTR6 i-	BLK
c3	P6-5	SHLD6 I	SHLD
c3	P6-6	SHLD6 Q	SHLD
Z3	P6-7	MTR6 Q+	RED
Z4	P6-8	MTR6 Q-	BLK
Z5	P6-1	ENC6_PWR	RED
Z6	P6-2	ENC6_GND	BLK
a1	P7-3	MTR7 i+	RED
a2	P7-4	MTR7 i-	BLK
c2	P7-5	SHLD7 I	SHLD
c2	P7-6	SHLD7 Q	SHLD
a3	P7-7	MTR7 Q+	RED
a4	P7-8	MTR7 Q-	BLK
a5	P7-1	ENC7_PWR	RED
a6	P7-2	ENC7_GND	BLK
b1		NC	
b2		NC	
c1		NC	
c1		NC	
b3		NC	
b4		NC	
b5		NC	
P0-b6		NC	

FIGURE 38: PSM INTERFACE CONNECTOR PINOUT.

2 4 19

WIRE TABLE						
FROM	TO	DESC	COLOR	CONTACT TYPE	AWG	REMARKS
P0-A1		NC				
A2		NC				
A3		NC				
A4		NC				
A5		NC				
A6		NC				
B1		NC				
B2		NC				
B3	B2-2	BRAKE2 -	BLK			
B4	B2-1	BRAKE2 +	RED			
B5	P2-11	MTR2 -	BLK			
B6	P2-12	MTR2 +	RED			
C1	P24-2	MTR4 -	BLK			
C2	P24-1	MTR4 +	RED			
C3	P1-12	MTR1 +	RED			
C4	P1-11	MTR1 -	BLK			
C5		NC				
C6		NC				
D1	B3-1	BRAKE3 +	RED			
D2	B3-2	BRAKE3 -	BLK			
D3		NC				
D4		NC				
D5	B1-1	BRAKE1 +	RED			
D6	B1-2	BRAKE1 -	BLK			
E3	P3-12	MTR3 +	RED			
E4	P3-11	MTR3 -	BLK			
E1		POT1 SHLD	SHLD			
E2	P11-1	POT1 REF	RED			
F1	P11-3	POT1 GND	BLK			
F2	P11-2	POT1 WIPER	WHT			
F3		POT2 SHLD	SHLD			
F4	P12-1	POT2 REF	RED			
G3	P12-3	POT2 GND	BLK			
G4	P12-2	POT2 WIPER	WHT			
E5	P13-4	POT3 SHLD	SHLD			
E6	P13-1	POT3 REF	RED			
F5	P13-3	POT3 GND	BLK			
F6	P13-2	POT3 WIPER	WHT			
G1	P14-4	POT4 SHLD	SHLD			
G2	P14-1	POT4 REF	RED			
H1	P14-3	POT4 GND	BLK			
H2	P14-2	POT4 WIPER	WHT			
H3		NC				
H4		NC				
J3		NC				
J4		NC				
G5		NC				
G6		NC				
H5		NC				
H6		NC				
J1		NC				
J2		NC				
K1		NC				
K2		NC				
J5		NC				
J6		NC				
K5		NC				
K6		NC				

19

WIRE TABLE						
FROM	TO	DESC	COLOR	CONTACT TYPE	AWG	REMARKS
P0-L1		NC				
M1						
N1						
L2		NC				
M2		NC				
N2		NC				
K3	S1-1	SJ1_RELn	RED			
L3	S1-2	SJ1_GNDn	BLK			
M3	S1-4	GND	BLK			
N3	S1-3	SJ1_REL	RED			
K4	S2-3	CAM_CLTCH	RED			
L4	S2-4	CAM_GNDn	BLK			
M4	S2-2	GND	BLK			
N4	S2-1	CAM_CLTCHn	RED			
L5		NC				
M5		NC				
N5	OVERALL SHLD	OVERALL SHLD	BLK			
L6	P0-M6	ARM PRESENTn	BLK			
M6	P0-L6	GND	BLK			
N6	OVERALL SHLD	OVERALL SHLD	BLK			
P1		NC				
R1		NC				
S1		NC				
P2		NC				
R2		NC				
S2		NC				
P3	S3-2	CLEAN SW GND	BLK			
R3	S3-1	CLEAN SW	RED			
P4		NC				
R4		NC				
S3		NC				
T3		NC				
S4		NC				
T4		NC				
P5		NC				
R5		NC				
S5		NC				
T5		NC				
P6		NC				
R6		NC				
S6		NC				
P0-T6		NC				

19

WIRE TABLE						
FROM	TO	DESC	COLOR	CONTACT TYPE	AWG	REMARKS
P0-U1	P1-3	ENC1 I+	RED			
U2	P1-4	ENC1 I-	BLK			
T2	P1-5	SHIELD1 i	SHLD			
T2	P1-6	SHIELD1 Q	SHLD			
U3	P1-7	ENC1 Q+	RED			
U4	P1-8	ENC1 Q-	BLK			
U5	P1-1	ENC1_PWR	RED			
U6	P1-2	ENC1_GND	BLK			
V1	P2-3	ENC2 I+	RED			
V2	P2-4	ENC2 I-	BLK			
T1	P2-5	SHIELD2 i	SHLD			
T1	P2-6	SHIELD2 Q	SHLD			
V3	P2-7	ENC2 Q+	RED			
V4	P2-8	ENC2 Q-	BLK			
V5	P2-1	ENC2_PWR	RED			
V6	P2-2	ENC2_GND	BLK			
W1	P3-3	ENC3 I+	RED			
W2	P3-4	ENC3 I-	BLK			
c6	P3-5	SHIELD3 I	SHLD			
c6	P3-6	SHIELD3 Q	SHLD			
W3	P3-7	ENC3 Q+	RED			
W4	P3-8	ENC3 Q-	BLK			
W5	P3-1	ENC3_PWR	RED			
W6	P3-2	ENC3_GND	BLK			
X1	P44-1	ENC4 I+	RED			
X2	P44-2	ENC4 i-	BLK			
c5	P44-3	SHIELD4 I	SHLD			
c5	P34-3	SHIELD4 Q	SHLD			
X3	P34-1	ENC4 Q+	RED			
X4	P34-2	ENC4 Q-	BLK			
X5	P54-1	ENC4_PWR	RED			
X6	P54-2	ENC4_GND	BLK			
Y1		NC				
Y2		NC				
c4		NC				
c4		NC				
Y3		NC				
Y4		NC				
Y5		NC				
Y6		NC				
Z1		NC				
Z2		NC				
c3		NC				
c3		NC				
Z3		NC				
Z4		NC				
Z5		NC				
Z6		NC				
a1		NC				
a2		NC				
c2		NC				
c2		NC				
a3		NC				
a4		NC				
a5		NC				
a6		NC				
b1		NC				
b2		NC				
c1		NC				
c1		NC				
b3		NC				
b4		NC				
b5		NC				
P0-b6		NC				

FIGURE 39: ECM INTERFACE CONNECTOR PINOUT.

Key:

MTRx +/-	Motor ‘x’ Positive/Negative	Positive/Negative terminal of motor on joint ‘x’
POTx	Potentiometer ‘x’	Potentiometer in the joint ‘x’
ENCx Q/i +/-	Encoder ‘x’ channel Q/i Positive/Negative	Differential signal of the channels from Encoder on joint ‘x’
SLAVE CLUTCH	Slave clutch	Switch for Clutching the Instrument
SJ2_REL	Setup Joints Release	Release Switch for clutching setup joints
ST ADAP	Sterile Adapter	Detects the presence of sterile adapter
INST LOOP BACK	Instrument loop back	Used to detect the presence of instrument
REF	Reference	Reference voltage
SHLD	Shield	Shielding for signals
PWR	Power	Power supply
GND	Ground	Ground terminal

APPENDIX C

Kinematic parameters

Disk numbering:

8mm Large Needle Driver (Part number: 400006)

Coupling matrix:

	Disk 1	Disk 2	Disk 3	Disk 4
Roll	-1.56323325	0.0	0.0	0.0
Pitch	0.0	1.01857984	0.0	0.0
Yaw	0.0	-0.830634273	0.608862987	0.608862987
Grip	0.0	0.0	-1.21772597	1.21772597

Denavit-Hartenberg parameters:
("*l*" is x-axis offset, "*a*" is x-axis rotation, "*d*" is z-axis offset, "*q*" is z-axis rotation)

Frame	l_i [m]	a_i	d_i [m]	q_i
1	0.0	0.0	0.4162	q_{roll}
2	0.0	-90°	0.0	q_{pitch} - 90°
3	0.0091	-90°	0.0	q_{yaw} - 90°
4	0.0	-90°	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0

Joint Signal Range:

	Roll	Pitch	Yaw	Grip
Upper Limit	260°	80°	80°	30°
Lower Limit	-260°	-80°	-80°	0°

Torque Limits:

	Roll [Nm]	Pitch [Nm]	Yaw [Nm]	Grip [Nm]
Upper Limit	0.33	0.25	0.2	0.16
Lower Limit	-0.33	-0.25	-0.2	-0.16

List of Instruments Compatible with Large Needle Driver Coupling Matrix:

Instrument Part Number	Instrument Name
400006	8mm Large Needle Driver
400036	8mm Debakey
400049	8mm Cadiere
400033	8mm Black Diamond Micro Forceps
400001	8mm Potts Scissors
400178	8mm Curved Scissors
400181	8mm Resano
400048	8mm Long Tip Forceps
400179	8mm Mono Curved Shears (MCS)
400007	8mm Round Tip Scissors
400121	8mm Fine Tissue Forceps
400190	8mm Cobra Grasper
400203	8mm Pericardial Dissector

8mm Prograsp (Part number: 400093)

Coupling matrix:

	Disk 1	Disk 2	Disk 3	Disk 4
Roll	-1.563131313	0.0	0.0	0.0
Pitch	0.0	1	0.0	0.0
Yaw	0.0	-0.5067567568	-0.5135135135	-0.5135135135
Grip	0.0	0.0	-0.5278987546	0.5278987546

Denavit-Hartenberg parameters:
("*l*" is x-axis offset, "*a*" is x-axis rotation, "*d*" is z-axis offset, "*q*" is z-axis rotation)

Frame	l_i *[m]*	a_i	d_i *[m]*	q_i
1	0.0	0.0	0.4162	q_{roll}
2	0.0	-90°	0.0	q_{pitch} - 90°
3	0.0107	-90°	0.0	q_{yaw} - 90°
4	0.0	-90°	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0

Joint Signal Range:

	Roll	Pitch	Yaw	Grip
Upper Limit	260°	70°	73°	54.4826°
Lower Limit	-260°	-70°	-73°	0°

Torque Limits:

	Roll [Nm]	Pitch [Nm]	Yaw [Nm]	Grip [Nm]
Upper Limit	0.33	0.25	0.24	0.45
Lower Limit	-0.33	-0.25	-0.24	-0.45