Technical Report

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Staübli work-cell: General description and operation

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Abstract

This technical report provides all the information necessary to operate all the elements that integrate the Staübli work-cell at the perception and manipulation laboratory at IRI. A detailed description of each of the robots, safety features, sensors and actuators available at the work-cell is presented. Special attention is paid to the integration of the safety features integrated into the operation of the robots of the work-cell. Also, for maintenance purposes and future upgrades, a detailed description of the electrical wiring of the control box, as well as its input an output connectors, is presented.

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1 Introduction

The perception and manipulation laboratory at IRI has a work-cell build around two Staübli RX60 serial manipulators with six degrees of freedom each. This work-cell has been extended over the years with a custom two degrees of freedom planar XY robot build on top of the whole cell, two simple grippers placed at the last joint of each of the Staübli robots and a six degrees of freedom force and torque sensor that can be placed in any manipulator.

The safety features integrated into the work-cell include a laser curtain that covers all the perimeter of the work-cell, two mechanical fuses at the end effector of each Staübli robot to cut power in case of excessive force and also several emergency stop buttons to be used by human operators: one for each robot and another one for the whole work-cell.

One of the main problems to set this work-cell in working order was that most of the devices listed before were not operational or were not even installed, and the ones that were, had some software and hardware requirements that made it very difficult to integrate them into the current software framework used at the Institute (the ROS middleware [8]).

So, it was decided to develop a new controller system capable of managing all the work-cell devices (robots, sensors, actuators and safety features), and integrate them in a homogeneous framework that made it easy for any one at IRI to use them. This work has been divided into two technical reports, this one which covers the work-cell structure, integration of all the devices and operation manual, and [7] which covers the design and development of an expansion board for an existing embedded controller.

This technical report is structured as follows. In section 2 each of the main elements of the work-cell is presented, and next, special attention is made to the safety features and how they are interconnected in section 3. Also, Appendices A and B present detailed information of the connector placement and electrical wiring respectively for easy maintenance and future upgrades.

2 Work-cell description

Fig. 1 shows the Staubli work-cell. This cell includes three robots: two RX60 Staübli serial manipulators (see section 2.1 for more details) and an XY planar robot (see section 2.2 for more details). Additionally, the work-cell also has a simple gripper (see section 2.3 for more details) and a mechanical fuse (see section 3.3 for more details) for each of the staübli robots, and a single force and torque sensor (see section 2.4 for more details).

The Staübli work cell has two modes of operation: the cell mode on which all robots operate in concert in order to accomplish a task, and the independent mode, in which each robot can operate on its own. Depending on the operation mode selected, the safety features presented in section 3 have different behaviors.

Table 1 and Table 2 show the behavior of all the safety features for each one of the robots for the cell mode and the independent mode respectively. The grayed safety features on these tables can be disabled in order to bypass them in the emergency stop chain of the robots.

As shown in Table 1, in cell mode, the activation of any safety feature stops the normal operation of all robots.

As shown in Table 2, in independent mode, each robot is only stopped by their associated safety features, except for the Laser curtain and the Cell emergency stop buttons, which affect all the robots.

The selection between the two modes, and the by-pass of the laser curtain and/or the mechanical fuses is done through a set of switches in a control pendant attached to the control box (see section 2.6 for more details).

Figure 1: Picture of the actual Staübli work-cell, with the two Staübli RX60B robot at the center, and the XY robot at the top.

2.1 Staübli robots

The two RX60B Staübli robots in the work-cell are industrial serial manipulators with 6 degrees of freedom each. Each joint use a brushless DC motor with and absolute encoder which make it possible to know the absolute position of the end effector at any time. The main features of the Staübli RX60 robots are listed in Table 3. For a more detailed description of the Staübli robot, see its technical manual, available in paper at the Perception and Manipulation Laboratory.

Each Staübli robot may have a mechanical fuse and a simple gripper attached as the end effector, and optionally a force and torque sensor. These devices require both electrical (power and signal) and pneumatic connections to operate. Instead of having cables and tubes hanging from the end effector of the manipulator, the robot itself has internal wiring and tubing between the base and the forearm joint, so that no external cables or tubes may interfere with the motion of the robot.

The electrical connector for the forearm is a series 423 miniature connector from Binder (model number 99-5662-15-19), and the connector for the base is also a series 423 miniature connector from Binder (model number 99-5661-75-19). An angled connector is used in the forearm to reduce possible collisions as much as possible. The connector at the base is straight.

Fig. 2 shows the wiring diagram between the base and forearm connectors for all the devices at the end effector of the manipulators. Both robots have the same wiring.

In Fig. 2, the letter on top of each wire indicates the pin connector label used for each signal. The colors of the conductors used for each signal is shown between parenthesis at the forearm connector side. The connectors provide up to 13 wires which can handle up to 1 A at 60 V and 2 shielded twisted pairs.

The gripper uses 4 wires (D,E,F and G) to carry the control signals of the stepper motor.

Table 1: Behavior of all the safety features in the cell operating mode.

	Left Staübli ES	**Right Staübli ES**	**XY robot ES**	**Laser Curtain**	**Cell ES**	**Left Mech. Fuse**	**Right Mech. Fuse**
Left Staübli	X	X	X	X	X	X	X
Right Staübli	X	X	X	X	X	X	X
XY Robot	X	X	X	X	X	X	X

Table 2: Behavior of all the safety features in the independent operating mode.

	Left Staübli ES	**Right Staübli ES**	**XY robot ES**	**Laser Curtain**	**Cell ES**	**Left Mech. Fuse**	**Right Mech. Fuse**
Left Staübli	X			X	X	X	
Right Staübli		X		X	X		X
XY Robot			X	X	X		

The power requirements for these signals match the power capabilities of the Satübli wiring presented before. The mechanical fuse uses 2 wires (H and I) for the internal switch used to notify over-force at the end effector.

Finally, the force and torque sensor uses 5 wires. Two of these wires (B and C) are used to carry the power supply to the sensor, whose power requirements are far below the power capabilities of the Staübli wiring. For the serial interface signals used to configure the sensor and retrieve data, one of the two available shielded twisted pairs is used (O, P and T, being the later the shield connected to ground.

The wires not shown in Fig. 2 are left unconnected and they can be used in the future to carry power or control signals to new devices attached at the end effector of the Staübli robots.

To provide the necessary air pressure to operate the mechanical fuses, a silent compressor is used (model KOSA-15A from SilAir), which provides up to 8 $bars$ with a maximum flow rate of 12 l/min. As will be presented later in section 3.3, each mechanical fuse accepts a pressure

Table 3: Main features of the RX60B Staübli robots.

Feature	**value**
Num. d.o.f.	6
Max. Payload (high speed)	2.5 kg
Max. Payload (low speed)	4.5 kg
Repeatability	$\pm 0.02\, mm$
Max. Linear Speed	8 m/s

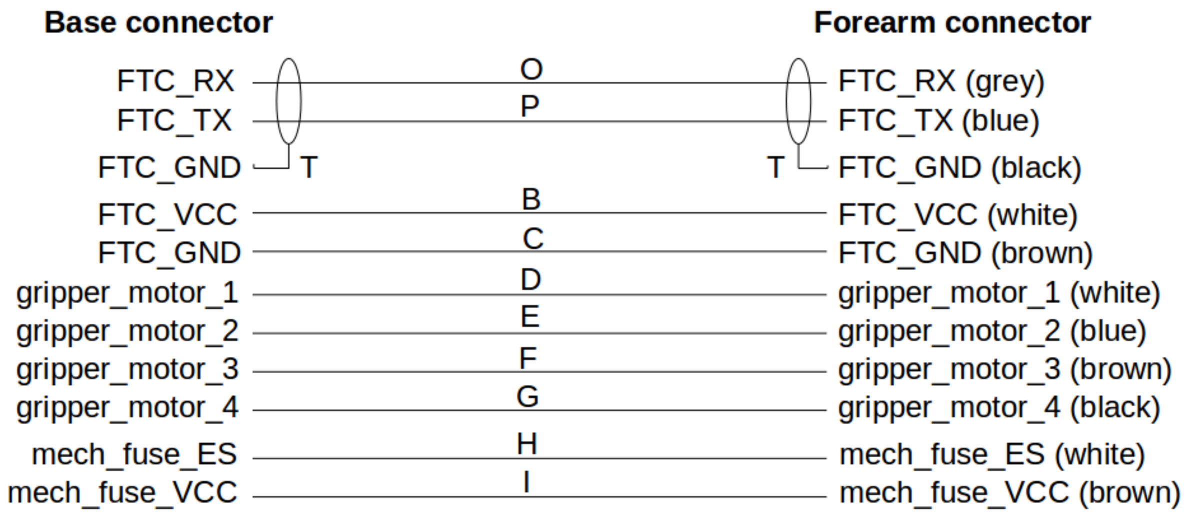


Figure 2: Wiring between the base and the forearm to carry the necessary power and control signal to the devices at the end effector of the robot.

of up to 6 bar so this compressor is enough to operate one mechanical fuse at its full pressure range or both up to 4 bar each.

To carry the pneumatic pressure from the compressor to the mechanical fuse at the end effector of the robot, first the output is split in two to reach each of the robot bases using a T adapter. The robot provides two different circuits to reach the forearm, one with internal electro-valves (P1) and the other without (P2). The one used in this case is P2 because it is not possible to control the valves with the available software. From the forearm of the robot to the actual mechanical fuse a single pneumatic tube is used with enough margin to allow free motion of the last degrees of freedom of the robot.

All the pneumatic tubing used has 8 mm in diameter and $M5$ racors are used for the robot and compressor connections. The connection to the mechanical fuse is by pressure. Finally, close to the base of each robot, so that it can be easily accessed, a release valve has been placed. This valve is necessary in order to accumulate enough pressure at startup to activate the sensor due to the limited flow the compressor is capable of providing. Without this valve the air will pass through the mechanical fuse without engaging it.

See section 3.1 for a description of the safety features provided by the Staübli robot.

2.1.1 Software

Each Staübli robot is managed by a dedicated control box named CS-8 located at either side of the work-cell. These control boxes have the power stages for each of the joints of the robot and also an embedded computer to perform the control of the manipulator.

The Staübli robots can be manually controlled, both in joint and Cartesian coordinates, using a control pendant connected to the control box. A part from standard configuration and motion controls, this pendant has an emergency stop button to stop the operation of the robot at any time, and also a dead man switch that must be pressed at all times while controlling the robot, or otherwise it will stop immediately. See the paper copy of the Staübli robots manual available at the laboratory for more information on the manual operation of the robot.

The robots can also be remotely controlled by a computer in automatic mode. In this case the Ethernet interface of the embedded computer of each CS-8 control box is used to send the configuration and motion commands to the robots using the SOAP library, provided by the robot manufacturer. This library has been integrated into a Labrobotica driver with a more user friendly interface. Fig. 3 shows the software structure developed for the Staübli robots.

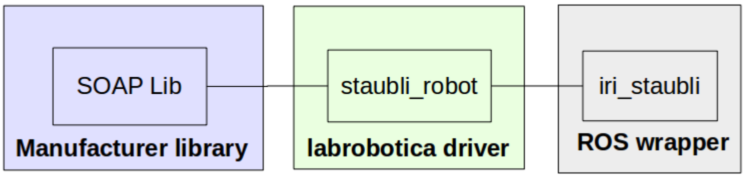


Figure 3: Software structure developed for the Staübli robots, including the Labrobotica driver and the ROS wrapper.

The SOAP library is divided in several server levels, each one providing a set of features. Due to the limitations of the embedded computer on the CS-8 controller box, only levels 0, 1 and 3 are supported, however, the features available within these levels are more than enough for the current requirements of the Staübli work-cell. In the future it may be necessary to upgrade the internal computer to get more features.

The SOAP library requires to work with a lot of quite complex data structures to access the robot's functionality. Furthermore, the available documentation on the functions and data structures is almost inexistent, so, the Labrobotica layer was designed to embed all the data structure handling and provide a simpler public interface to the user. Also, this driver implements two different threads, one to periodically get the current position of the robot, both in joint and Cartesian space, and the second one to handle the command queue of the robot to execute trajectories.

The main features provided by the Labrobotica driver are listed below (the complete documentation for this library can be found at [5]).

- Choose the desired robot configuration. Like most serial manipulators, the solution of the inverse kinematics may have several solutions, and it is possible to select which configuration is preferred. This include the configuration of the shoulder, elbow and wrist joints.

- Choose and configure how the different segments of a trajectory are blended together to achieve a smooth motion. In general, when using blending, the robot does not go through all the intermediate target points.

- Move the frame associated to the end effector of the robot to a desired position in Cartesian space. The manufacturer library allows to define new frames depending on the end effector used, but this feature is not supported by the Labrobotica driver.

- Move the robot in joint space, giving the desired angle for each of the joints of the robot. It is also possible to load several joint configurations to be executed sequentially to follow a desired trajectory. The sequence can be stopped, resumed or canceled at any time.

- Get the current angle of all the joints and also the current Cartesian position for the end effector of the robot.

- Compute the Cartesian position of the end effector for a given set of joint angles (forward kinematics) and also the necessary joint angles to get to a desired Cartesian position (inverse kinematics).

To integrate this driver into the general middleware framework used at IRI, a ROS wrapper has been developed. In this case, the wrapper complies with the ROS industrial specifications, which defines a set of common interfaces for control and feedback information to facilitate the interoperability between robots from different vendors (see [9] for more details).

This ROS layer was developed by the Student Dídac Marquès as part of his final year project. All the details of the design and implementation of this wrapper can be found in [2], as part of the project documentation. Here, only a brief description is given for completeness.

The ROS wrapper, publishes the following topics:

- **feedback_states (control_msgs/FollowJointTrajectoryFeedback)**: This topic is used to provide information about the current and desired position, velocity and acceleration (if available), and their differences, for all the joints of the robot. This topic is needed to comply with the ROS industrial specification.
- **robot_status (industrial_msgs/RobotStatus)**:This topic provides the current status of critical robot parameters. The current implementation of this wrapper only supports the moving and error status, all the other status are not used. This topic is needed to comply with the ROS industrial specification.
- **tcp_pose (geometry_msgs/PoseStamped)**: This topic provides the current Cartesian position of the end effector with respect to the base. This topic is not required by the ROS industrial specification.
- **joint_states (sensor_msgs/JointState)**: This topic provides information of the current position , velocity and effort for all joints. This topic is used by the robot_state_publisher node to broadcast the current transformations between all joint. Although this is a quite standard topic, it is also required by the ROS Industrial specification.

The ROS wrapper, subscribes to the following topics:

- **enable_power (std_msgs/Bool)**: This subscriber is intended to enable or disable the power stages for the joints. By default the power is turned off, and in order to move, it must be turned on using this service. This service is not required by the ROS Industrial specification.
- **joint_command (trajectory_msgs/JointTrajectoryPoint)**: This subscriber is intended to provide a way to control the robot in real time, streaming new motion commands as they are generated or required. This topic is needed to comply with the ROS industrial specification.
- **jointPathCommand (trajectory_msgs/JointTrajectory)**: This subscriber is used to execute a pre-calculated joint trajectory on the robot. The subscriber's callback function starts the motion, but it does not wait for the trajectory to end. The status topics should be used to know the current state of the robot. This topic is needed to comply with the ROS industrial specification.

The ROS wrapper has the following service servers:

- **jointPathCommands (industrial_msgs/CmdJointTrajectory)**: This service is functionally equivalent to the jointPathCommand subscriber. The service can be used to get a confirmation that the robot actually received the motion trajectory and it is being executed. This service is required by the ROS Industrial specification.
- **stop_motion (industrial_msgs/StopMotion)**: This service stops the motion of the robot at any time. This service is required by the ROS Industrial specification.

- **GetPositionIK (moveit_msgs/GetPositionIK)**: This service may be used to get the solution of the inverse kinematic problem for the Staübli robot, given a desired Cartesian position for the end effector. The ROS Industrial specification requires the existence of this feature, but it recommends using a plug-in instead of a service to avoid the communications overhead.

- **move_in_joints (iri_common_drivers_msgs/QueryJointsMovement)**: This service is used to move the joints of the robot to a desired position. The service call start the motion of the robot, but it does not wait for the robot to reach the desired position. The status topics should be used to know the current state of the robot.

  This service is equivalent to the joint_command subscriber required by the ROS Industrial specification, but it is intended to provide compatibility with other serial manipulators used at the Perception and Manipulation Laboratory at IRI.

- **move_in_cart (iri_common_drivers_msgs/QueryCartesianMovement)**: This service is used to move the end effector of the robot to a desired Cartesian position. The service call start the motion of the robot, but it does not wait for the robot to reach the desired position. The status topics should be used to know the current state of the robot.

The ROS wrapper has the following action servers:

- **follow_joint_trajectory (control_msgs/FollowJointTrajectory)**: This action is used to execute a pre-calculated trajectory in joint space. Its functionality is equivalent to the jointPathCommand subscriber and the jointPathCommand service, but it provides specific feedback while the trajectory is in progress, and also notifies the corresponding action client when the trajectory ends, giving information of how it ended.

  This action is not required by the ROS Industrial specification, but it is intended to provide compatibility with other serial manipulators used at the Perception and Manipulation Laboratory at IRI.

The ROS wrapper has the following parameters:

- **IP_address (default: 127.0.0.1)**: This is the IP address of the embedded computer of the Staübli controller. This parameter is required by the ROS Industrial Specification. The IP addresses of each robot in the Staübli work-cell at IRI are shown in Table 4.

Table 4: IP addresses of both Staübli robots in the work-cell.

left Staübli	192.168.100.233
right Staübli	192.168.100.232

2.2 XY robot

As shown in Fig. 1, on top of the work-cell there is a custom built XY robot with 2 degrees of freedom. The main function of this robot is to move cameras, lights or other devices and sensors to a desired position inside the work-cell, depending on the task carried out by one or both Staübli robots.

This robot was designed and built as part of the final year project of the student Ferran Cortes Celigueta. All the details of the design and construction of this robot can be found in [3], as part of the project documentation. In this section, only the most relevant information is provided for completeness.

Fig. 4 shows a schematic representation of the robot. The end effector of the robot, where the desired device or sensor would be attached, is colored in dark gray. It moves along the x axis using a linear transmission actuated by a DC brushed motor, which functions both as an actuator and as an structural element.

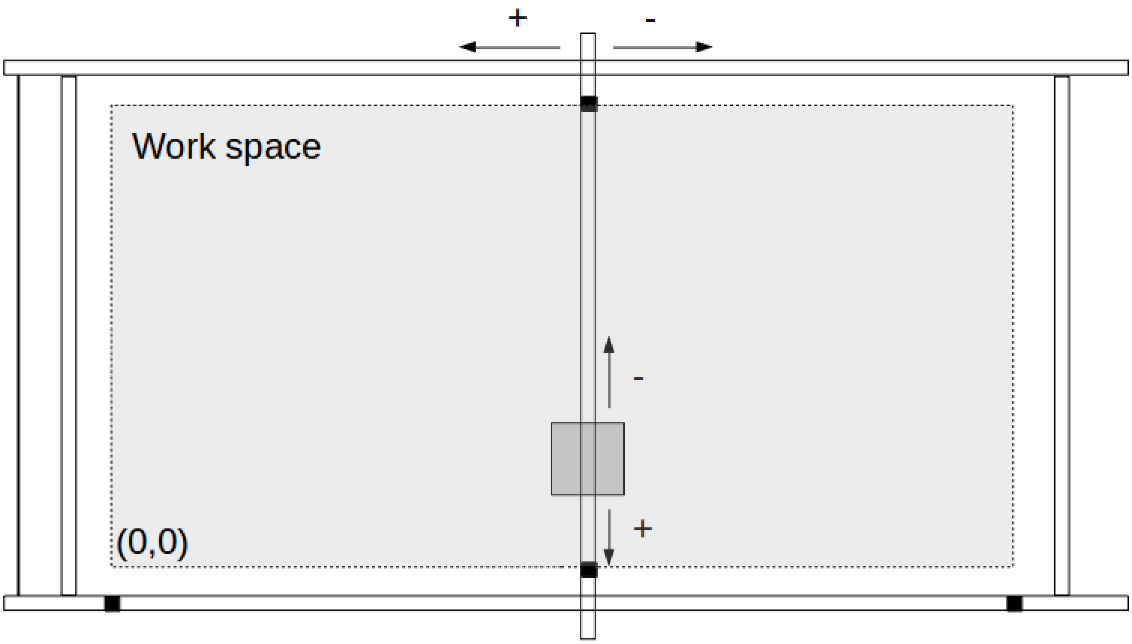


Figure 4: A schematic representation of the XY robot developed at IRI.

The whole set moves along the y axis using a second linear transmission actuated by an other DC brushed motor. This second transmission is made up of two separate parts connected by a transmission axle to provide traction to both sides of the end effector set.

The work space of the robot is shown as a shaded area in Fig. 4, and its dimensions are determined by the position of the motion limit switches (shown as small black boxes). These limit switches can be moved to adjust the workspace to a specific task, however, the origin of the workspace is always at the lower left corner as shown in Fig. 4. The maximum dimensions of the workspace are shown in Table 5, together with other main features of the robot.

Table 5: Main features of the custom built XY robot.

Feature	**value**
Max. workspace x	1.4 m
Max. workspace y	1.8 m
Max. speed (x,y)	0.5 m/s
Max. Payload	5 kg
Resolution (x,y)	0.025 mm

Each axis is controlled separately using the MCDC2805 Motor controller from Faulhaber. This is a standalone controller which includes the power stage for the motor, the encoder and limit switches inputs, and implements both position and velocity control loops. Its main features are listed in Table 6.

Fig. 5 shows the wiring for each of the controllers. Two of the general purpose signals of the motor controller (FAULT and 3in) are used for the forward and reverse motion limit

Table 6: Main features of the MCDC2805 motor controller.

Feature	**value**
Supply voltage	12 V to 28 V
Max. continuous current	5 A
Max. peak current	10 A
Interface	serial with RS-232 levels
Encoder Input	Quadrature encoder without index ($F_{max} = 200\ kHz$)
Num. General Inputs	5

switches respectively. The used switches (NBB2-V3-E2 from Pepperl Fuchs) provide an open collector output, which requires a pull up resistor. These resistors are placed close to the switches themselves.

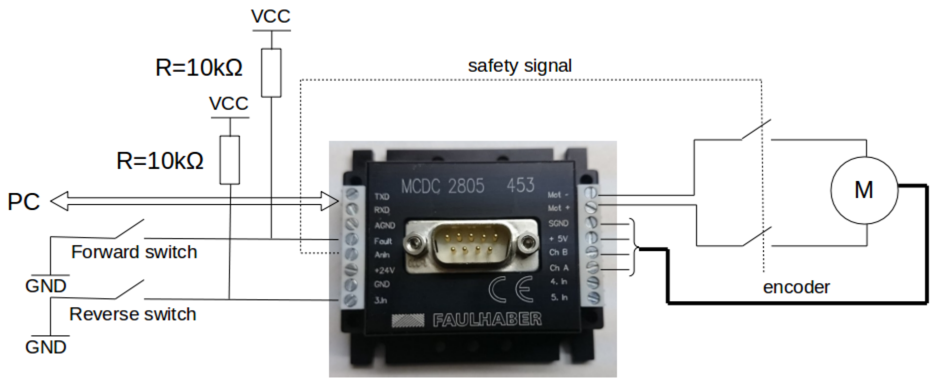


Figure 5: Wiring of the MCDC2805 controllers for the XY robot.

Each controller communicates with an external computer using a dedicated serial interface with RS-232 levels. For the Staübli work-cell, the two serial ports are routed to an embedded computer specially designed to handle the whole work-cell (see the technical report [7] for more details).

See section 3.2 for a description of the safety features provided by the XY robot. See Appendix B.4 for the connector pinout of the cables going between the XY robot and the control box.

2.2.1 Software

Each MCDC2805 driver is controlled individually by a labrobotica software driver that implements the communication between the embedded computer and the physical driver on an independent serial interface with RS-232 levels.

The xy_robot labrobotica driver creates two instances of the MCDC2805 software driver (one for each axis) and provides functions to move the robot's end effector in the Cartesian space. The structure of the software is shown in Fig. 6

The main features provided by the Labrobotica driver are listed below (the complete documentation for this library can be found at [6]):

- Perform a homing operation in which the end effector is moved to the origin direction until the motion limit switches are reached. At this point, the robot stops and sets the current position as the new home position by reseting the encoder step counters.

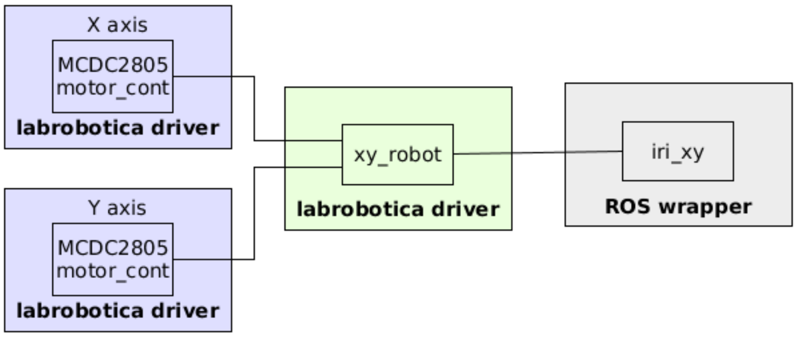


Figure 6: Software structure of the XY robot, containing the motor controllers for each axis, the labrobotica robot driver and the ROS wrapper.

- Choose and configure how the different segments of a trajectory are blended together to achieve a smooth motion. In general, when using blending, the robot does not go through all the intermediate target points.
- Move the frame associated to the end effector of the robot to a desired position in Cartesian space. It is also possible to load several Cartesian configurations to be executed sequentially to follow a desired trajectory. The sequence can be stopped, resumed or canceled at any time.
- Move the robot in joint space, giving the desired angle for each of the joints of the robot.
- Get the current angle of all the joints and also the current Cartesian position for the end effector of the robot.
- Compute the Cartesian position of the end effector for a given set of joint angles (forward kinematics) and also the necessary joint angles to get to a desired Cartesian position (inverse kinematics).

A ROS layer was developed to integrate the robot in the middleware framework as indicated in Fig. 6. The ROS wrapper, publishes the following topics:

- **joint_states (sensor_msgs/JointState)**: This topic provides information of the current position in meters for all joints. This topic is used by the robot_state_publisher node to broadcast the current transformation between each joint.
- **xy_angles (sensor_msgs/JointState)**:This topic provides information of the current position in angles for all joints.

The ROS wrapper has the following service servers:

- **move_Cartesian (iri_common_drivers_msgs/QueryJointsMovement)**: This service is used to move the joints of the robot to a desired position (in meters). The service call start the motion of the robot, but it does not wait for the robot to reach the desired position. The status topics should be used to know the current state of the robot.

The ROS wrapper has the following action servers:

- **follow_trajectory (control_msgs/FollowJointTrajectory)**: This action is used to execute a pre-calculated trajectory in joint space. It provides feedback while the trajectory is in progress and also notifies the corresponding action client when the trajectory ends, giving information of how it ended.

The ROS wrapper has the following parameters:

- **frame_id (default: robot_xy)**: Name of the frame associated to the origin of the robot

2.3 Grippers

The grippers used in the Staübli work-cell are the MEG50EC from Schunk, shown in Fig. 7. The gripper itself has no embedded controller, so an external one is used. This controller is the MEG-C also from Schunk which allows to control the stroke, force and speed of the jaws by means of analog signals. It also provides digital inputs to control the gripper functions (such as open, close and calibration), and digital outputs to report the status of the gripper. The current position of the jaws is reported also as an analog signal.

Figure 7: Gripper MEG50EC from Schunk.

The gripper can operate in two different modes: in position mode the jaws move to the desired position at the desired speed until the goal position is reached or the maximum desired force is exceeded. In force mode, the jaws either open or close the the maximum or minim position respectively until the maximum desired force is exceeded.

The gripper does not have any encoders (it uses a stepper motor) which make it necessary to perform a calibration procedure before it can be used in position mode. Otherwise, the behavior of the gripper will change depending on the initial position. However, it can be used in force mode without calibrating. The calibration procedure consists on moving the jaws to the maximum or minimum position until the maximum force is exceeded.

There are two grippers available at the Perception and Manipulation Laboratory at IRI, one for each of the Staübli robots, if necessary. The main feature of the MEG50EC grippers are shown in Table 7. See the product manual for more detailed information ([10]).

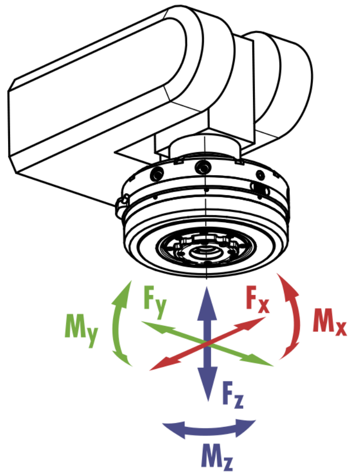
Table 7: Main features of the MEG50EC gripper.

Feature	**Value**
Power supply	24 V
Position range	8 mm
Force range	110 N
Speed range	6 mm/s to 32 mm/s
Weight	0.71 kg

The control of these grippers is performed by an embedded computer specially designed to handle the whole work-cell (see the technical report [7] for more details).

The grippers do no provide any safety features nor they are affected by any other safety feature of the work-cell. See Appendix B.5 for the connector pinout of the cables going between the grippers and the control box.

(a) Picture of the FTCL50 force and torque sensor from Schunk.



(b) Reference systems used in the FTLC50 force and torque sensor.

Figure 8

2.4 Force and torque sensor

The force and torque sensor used is the FTCL50 from Schunk (shown in Fig. 8a), which has three degrees of freedom to measure forces and three more to measure torques, and also, it is capable of measuring the deformation of the sensor due to external action. Both data acquisition and sensor configuration is done through a high speed serial port interface with RS-232 logic levels.

Only one of this sensors is available at the Perception and Manipulation Laboratory at IRI, so only one of the Staübli robots will be able to sense forces and torques at its end effector. The main features of this sensor are shown in Table 8.

Table 8: Main features of the FTCL50 force and torque sensor.

Feature	**Value**
Force range (x,y,z)	$\pm 300\ N$
Torque range (x,y)	$\pm 7\ N$
Torque range (z)	$\pm 15\ N$
Deflection range (translatory)	$\pm 1\ mm$
Deflection range (rotational)	$\pm 1°$
Interface	serial RS-232 levels
Weight	$0.96\ kg$

See Fig. 8b for the coordinate system used to measure the forces, torques and deflections provided by the sensor.

The force and torque sensor does no provide any safety features nor it is affected by any other safety feature of the work-cell. See Appendix B.6 for the connector pinout of the cables going between the sensor and the control box.

2.4.1 Software

Fig. 9 shows the software structure developed for the force and torque sensor from SCHUNK. The Labrobotica layer handles all the low level serial port communications and provides a simple API to the user.

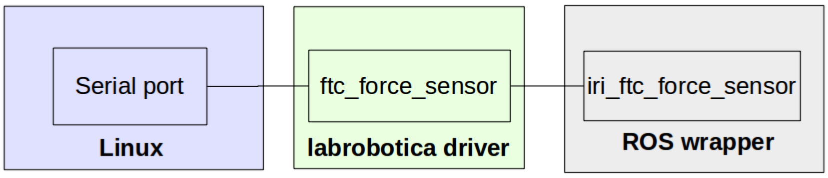


Figure 9: Software structure developed for the force and torque sensor.

This driver uses an internal thread to periodically get all the information on all the physical magnitudes (forces, torques, displacements and rotations) from the sensor. The main features provided by the Labrobotica driver are listed below (the complete documentation for this library can be found at [4]).

- Configure the desired baudrate of the serial communication. The maximum baudrate is 921600 bps.
- Configure the desired update rate of the sensor measures. The maximum rate is 1000 Hz.
- Calibrate the sensor to cancel out the effects of the gravity force on the sensor measures in its current configuration.
- Periodically updates the four physical magnitudes measured by the sensor (force, torque, displacement and rotation). An event is used to notify the user when new data is available, and avoid having to continuously poll the sensor.
- Provides static and dynamic information about the sensor. Static information include the hardware and software versions, and the maximum ranges for the four physical magnitudes measured, among others. The dynamic information includes, among others, the serial interface configuration, and the user selected ranges for the four physical magnitudes, which are a subset of the maximum ones.

A part from the standard ROS interface of topics, services and/or actions, the ROS wrapper shown in Fig. 9 uses the displacement and rotation information provided by the sensor to publish a transform between the sensor frame and the tool frame, which changes due to the external forces and torques. This can be useful when trying to position the end effector of the robot at a desired position and orientation under external forces.

The ROS wrapper, publishes the following topics:

- **tf_data (geometry_msgs/WrenchStamped)**: This topic publishes the force and torque measured from the sensor at the configured rate. The timestamp used in the message header is the one provided by the sensor, which is the one at which the sample was taken. This can be useful to synchronize the data from the sensor with the motion of the robot or with information from other sensors.

The ROS wrapper has the following service servers:

- **set_zero (std_srvs/Empty)**: This service is used to calibrate the zero of the sensor. When called, the currently measured forces and torques are canceled, effectively setting the output of the sensor to zero. This service can be called at any time.

The ROS wrapper has the following parameters:

- **serial_dev (default: /dev/ttyUSB0)**: This is the serial device used to communicate with the sensor. In the launch files for the Staübli work-cell, the sensor communication device is set to */dev/ttyO4*.
- **baudrate (default: 230400 bps)**: This is the desired speed in bits per second of the serial interface.
- **sensor_rate (default: 200 Hz)**: This is the desired update rate in Hertz of the force and torque information.
- **sensor_frame_id (default: /ftc_sensor)**: This is the base frame for the sensor, the one attached to the last link of the robot.
- **tool_frame_id (default: /ftc_tool)**: This is the frame where the end effector of the robot is actually attached. Its position and orientation changes due to external forces and torques, and this change is reported through a *tf* broadcast.

2.5 Power panel

At the front side of the Staübli work-cell, at the bottom left corner, there is the main power panel (shown in Fig. 10). This panel provides a main AC power switch, labeled *main power* in Fig. 10, to turn power on and off to the whole cell, except for the Staübli robots which have their own power switch at the corresponding CS-8 controller box. When the cell is powered up, the red light just above the switch should be lit.

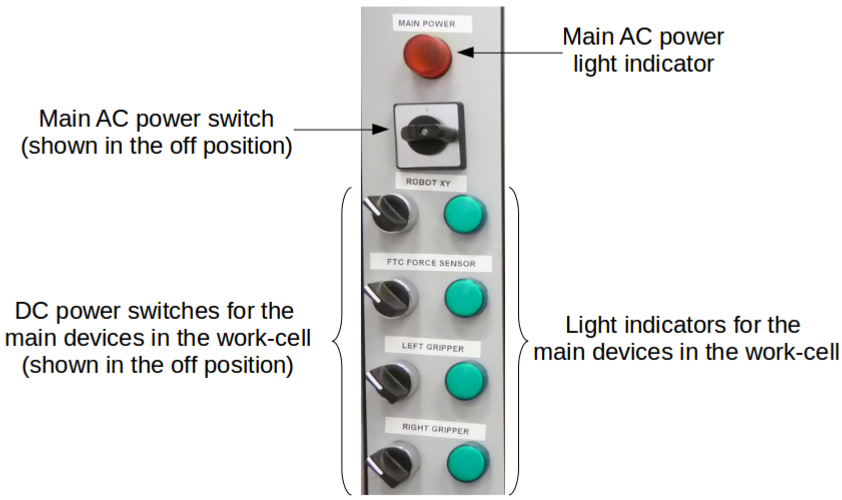


Figure 10: Power panel for the Staübli work-cell at the lower left corner of the front side of the cell.

The main power switch provides power to the internal 24 V DC power supply, which in turn powers all the devices in the control box. All the safety features described later in section 3 are powered as soon as the main power is turned on, because they are always needed. Other devices, like the XY robot, the force and torque sensor and both gripper may be needed depending on the application, so a dedicated power switch for each one is provided in the power panel shown in Fig. 10.

Next to each power switch there is a green light indicator to show the current power state of corresponding device, as shown in Fig. 10. The light should be lit when the power is on, except if the internal fuse, used to provide additional protection against unexpected surges, has blown for some reason. This makes it easier to track down and solve possible problems.

The embedded computer used to handle the whole cell starts booting just after the main power is turned on. To properly shutdown the Staübli work-cell, it is recommended to first log-in into the embedded computer and shut it down, and then turn off the power to the work-cell after a few seconds. Otherwise, the file system of the embedded computer may get corrupted.

See Appendix B.2 for the electric diagram of the power switches used for the Staübli work-cell.

2.6 Control pendant

The control pendant for the Staübli work-cell is shown in Fig. 11.

Figure 11: Frontal cover of the control pendant for the Staübli work-cell.

The main function of this control pendant is to provide to the user a simple and easy access to the main configuration options of the Staübli work-cell and also the current status of each of the elements on the cell. To this end, the control pendant provides the following features:

- Select the desired operation mode of the work-cell, either cell mode or independent mode. Two yellow light indicators show the current selected mode.
- By-pass switches to disable the use of the laser curtain and the mechanical fuses from the emergency stop chains where they are used. See sections 3.3 and 3.4 for more details on the by-pass function for these safety features.
- Light indicators to show the current status of each of the emergency stop chains available for the Staübli work-cell. See section 3.6 for more details on the available emergency stop chains.
- A button to re-arm the laser curtain emergency stop feature once it has been activated. See section 3.4 for more details.

To by-pass a safety feature, the corresponding switch should be placed on the right position. Fig. 11 shows all the by-pass switches on the left position, meaning that non of the safety features are by-passed. To select the cell operating mode, the left most switch must be on the left position, and the independent mode is selected when it is on the right position.

See Appendix B.10 for the electric diagram of the control pendant used for the Staübli work-cell, and also for the connector pinout of the cables going between the pendant and the control box.

3 Safety features

This section first describes all the safety features available in the work-cell from section 3.1 through 3.5. Then the actual emergency stop chains for both Staübli robots and the XY robot, and also the emergency stop chain for the whole cell are presented in section 3.6.

3.1 Staübli robots

Each Staübli robot has several safety features included in two symmetric emergency stop chains, and each one has two modes of operation: manual and automatic. The safety features are:

- **TPES** (control pendant emergency stop button): This signal is used in both modes of operation, and it is associated to the red button in the control pendant.

- **USER_ES1-2** and **USER_ES3-4** (user emergency stop signals): These signals are used in both modes of operation, and they are permanently bypassed in hardware to simplify the operation of the robot.

- **USER_EN1-2** (user enable signal): This signal is only used in manual mode, and it is permanently bypassed in hardware to simplify the operation of the robot.

- **DOOR** (controller door open switch): This signal is only used in automatic mode, and it is used by the work-cell safety features to halt the operation of the robot in case of any external problem.

- **BRS** (breaks active signal): This signal is used in both modes of operation, and it is associated with the power status of the robot, which can be controlled by software of by the control pendant.

Fig. 12 shows the simplified internal emergency stop chains for the Staübli robots used in the work-cell.

As shown in Fig. 12, the robot also provides a safety status output to notify external devices about the operational status of the robot. This signal takes into account the control pendant emergency stop button and the external emergency stop status when configured in automatic mode, but it ignores the state of the breaks and power status of the robot (BRS signal).

This external status signal is provided to the work-cell safety features to monitor the operational status of the robot and halt the operation of other robots when necessary. Note that in manual mode, the operator can control the robot using the control pendant independently from the external emergency stop signals.

See section 3.6 for information on how these safety features, and other safety features provided by the work-cell, have been integrated to build the available emergency stop chains. See Appendix B.3 for the connector pinout of the cables going between the staübli robots and the control box.

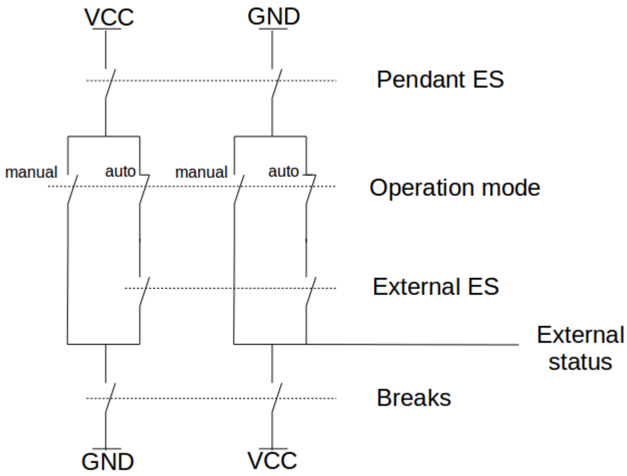


Figure 12: Simplified emergency stop chain for each of the Staübli robots.

3.2 XY robot

The original construction of the XY robot did not provide any safety features. In order to be able to stop the robot when necessary, a relay circuit has been added to the motor power lines as shown in fig. 5.

Cutting power from the motor instead of removing the power supply from the whole motor controller, has the advantage of keeping the communication alive between the controller and the software driver. This way, the control application will be able to handle the error condition properly, instead of crashing due to some communication error.

However, if the error is not handled by software and the previous motion command is not canceled, the motor will continue to move as soon as the power is restored to the motors. To avoid this, the same safety signal used to cut power is routed to the AnalogIn input of the controller as shown in Fig. 5, which, when properly configured, will stop the motor.

An external emergency stop button has been also added to allow the user to halt the normal operation of the robot whenever necessary. This button provides two separate circuits that are closed in normal operation, and open when the button is pressed to disable the emergency stop chains to which they are connected (see section B.7). One of the circuits is used for the XY robot emergency stop chain and the other for the emergency stop chain of the whole cell (see section 3.6 for more details).

See section 3.6 for information on how this safety feature, and other safety features provided by the work-cell, have been integrated to build the available emergency stop chains.

3.3 Mechanical fuse

The mechanical fuses used in the work-cell are the QS-25 from QuickStop (shown in fig. 13), which have a pneumatically sealed and pressurized chamber that is used to provide collision protection for the Staübli robots. When a collision occurs or the force at the end effector is too high, the seal instantly opens resulting in an immediate loss of pneumatic pressure in the chamber, leaving the end effector loose.

By varying the pneumatic pressure in the chamber the overload threshold can be easily adjusted to suit the requirements of each application. At the moment the pressure can only be adjusted manually, but it will be possible to do it electronically in the future, if needed.

The main features of the mechanical fuses used at the Staübli work-cell are shown in Table

Figure 13: Mechanical fuse QS-25 from QuickSTOP used at the end effector of the Staübli robots.

9.

Table 9: Main features of the QS-25 mechanical fuses from QuickStop.

Feature	**Value**
Compliance Angle	$\pm 5°$
Axial Compliance	$3.4\,mm$
Operating Pressure	$1\,bar$ to $6\,bar$
Weight	$0.26\,kg$
Response time	$< 15\,ms$
Moment trip point (x,y,z)	$1\,Nm$ to $6.4\,Nm$

Parallel to the mechanical release of the end effector, the mechanical fuse provides a normally closed electrical switch that can be included in an emergency stop chain. See Appendix B.8 for the connector pinout of the cables going between the two mechanical fuses and the control box.

The mechanical fuses may not always be installed at the end effector of the Staübli robots, depending on the application. In these cases, the normal operation of this safety feature can be by-passed to ensure the associated emergency stop chains continue to work properly whether the mechanical fuses are used or not. Each of the mechanical fuses can be by-passed by a dedicated selector in the control pendant of the work-cell (see section 2.6).

Fig. 14 shows a sketch of how the by-pass works. The selector switch is placed in parallel with the actual mechanical fuse switch, basically creating a logical OR function with both of them.

See section 3.6 for information on how this safety feature, and other safety features provided by the work-cell, have been integrated to build the available emergency stop chains.

As explained in section 2.1, the limited flow provided by the used compressor make it necessary to use a valve in order to accumulate enough pressure to activate the sensor. Therefore, to set up the mechanical fuses, first make sure the valve is closed and turn on the compressor (if it is not already on). After a few moments, open the valve and the device should engage. If not repeat this procedure, but waiting for a longer period of time before opening the valve.

3.4 Laser curtain

To avoid the presence of any object or person inside the workspace of the work-cell when the robots are moving, a laser curtain has been placed surrounding the whole cell. The selected laser curtain used is the SOLID-2 from Leuze Electronics. See [1] for the complete manual of this safety device.

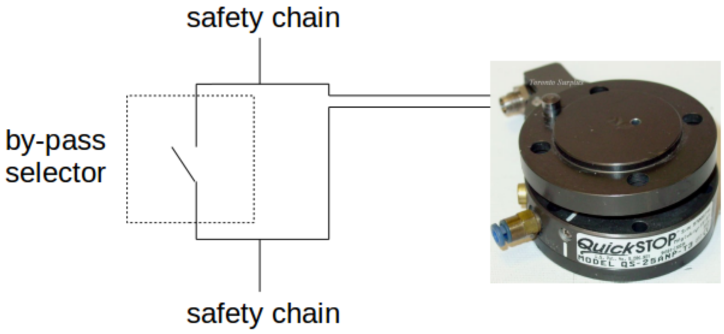


Figure 14: A sketch of the by-pass circuit used to disable the mechanical fuses in the emergency stop chains when they are not required.

Fig. 15 shows a sketch of the laser curtain safety feature implementation. See Appendix B.9 for the connector pinout of the cables going between the laser curtain and the control box.

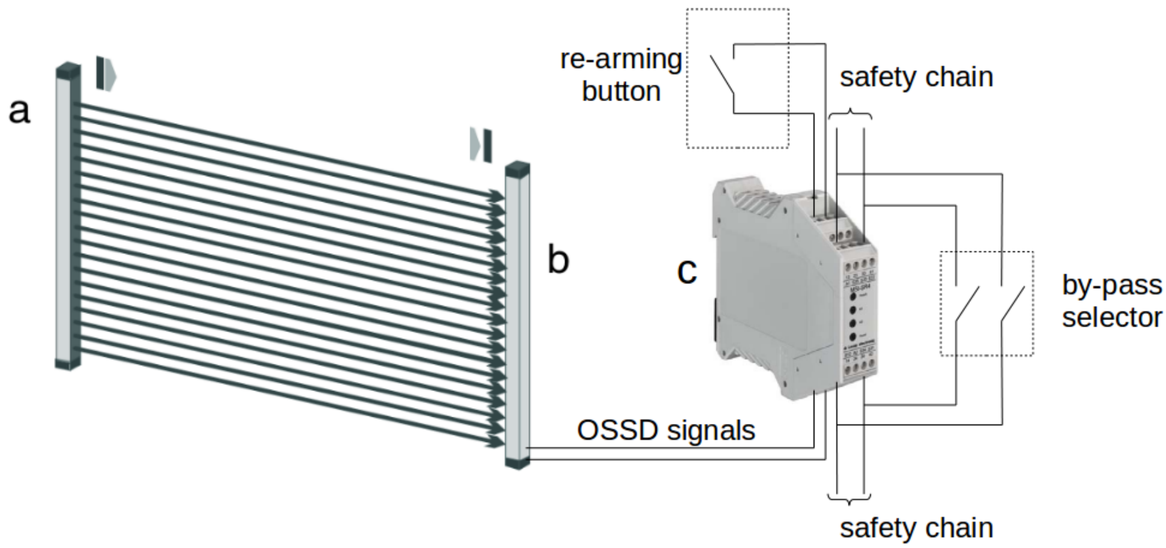


Figure 15: A sketch of the implementation of the laser curtain safety feature in the work-cell.

The laser curtain system consists of three devices:

- **Transmitter:** this device has several laser emitters that send pulsed and coded laser beams sequentially (device labeled a in Fig15). The code is used by the receiver to synchronize its operation with the transmitter.
- **Receiver:** this device receives the laser pulses from the transmitter and controls two safety outputs (OSSD) (device labeled b in Fig. 15). When all the laser beams are received, these two outputs have a high value, but when one or more of the beams are interrupted by an obstacle, these two outputs are tied to zero.
- **Emergency stop relay:** this device uses the two OSSD outputs of the receiver to control two parallel normally open circuits than can be integrated into the emergency stop chain

of the robots (device labeled c in Fig. 15). To increase the level of security, once opened due to an interference in the laser beams, the internal circuits can only be closed again by an external manual signal, even though the interference may have disappeared. This manual signal is implemented as a re-arming button placed at the control pendant of the work-cell (see section 2.6 for more details)

Initially, the laser curtain covered three of the four sides of the work cell (the fourth side being a wall) by using mirrors at two of the edges of the work-cell to reflect the laser beams. More recently, the two lateral sides have been covered with methacrylate panels, and the laser curtain is only used in the front side, without the mirrors.

The normal operation of the laser curtain can be by-passed as shown in Fig. 15. The by-pass selector switch is placed in the control pendant and works in parallel with the actual laser curtain switches, basically creating a logical OR function with both of them.

3.5 Cell emergency stop button

When working in the cell operating mode, it is more convenient to have a single emergency stop button to halt the operation of all the robots. However, in cell mode, the robot specific emergency stop buttons will also halt the normal operation of the whole cell, as shown in section 2.

This emergency stop button provides a single normally closed circuit for the whole cell emergency stop chain. See section 3.6 for detailed information of the emergency stop chains available. See Appendix B.7 for the connector pinout of the cables going between the emergency stop button and the control box.

3.6 Emergency stop chains

There are mainly one emergency stop chain for each of the robots of the work-cell: one for each of the Staübli robots (which are identical), and another one for the XY robot. Each chain has two parallel branches, one for each of the operation modes available. When the independent mode is selected, the safety devices marked in Table 2 in section 2 are used.

When the cell mode is selected, the emergency stop chain for any robot should be halted whenever any safety feature is activated, as shown in Table 1 in section 2. To simplify the implementation in this case, a fourth emergency stop chain has been implemented for the whole cell, and its output used in the second branch of the emergency stop chains of each robot.

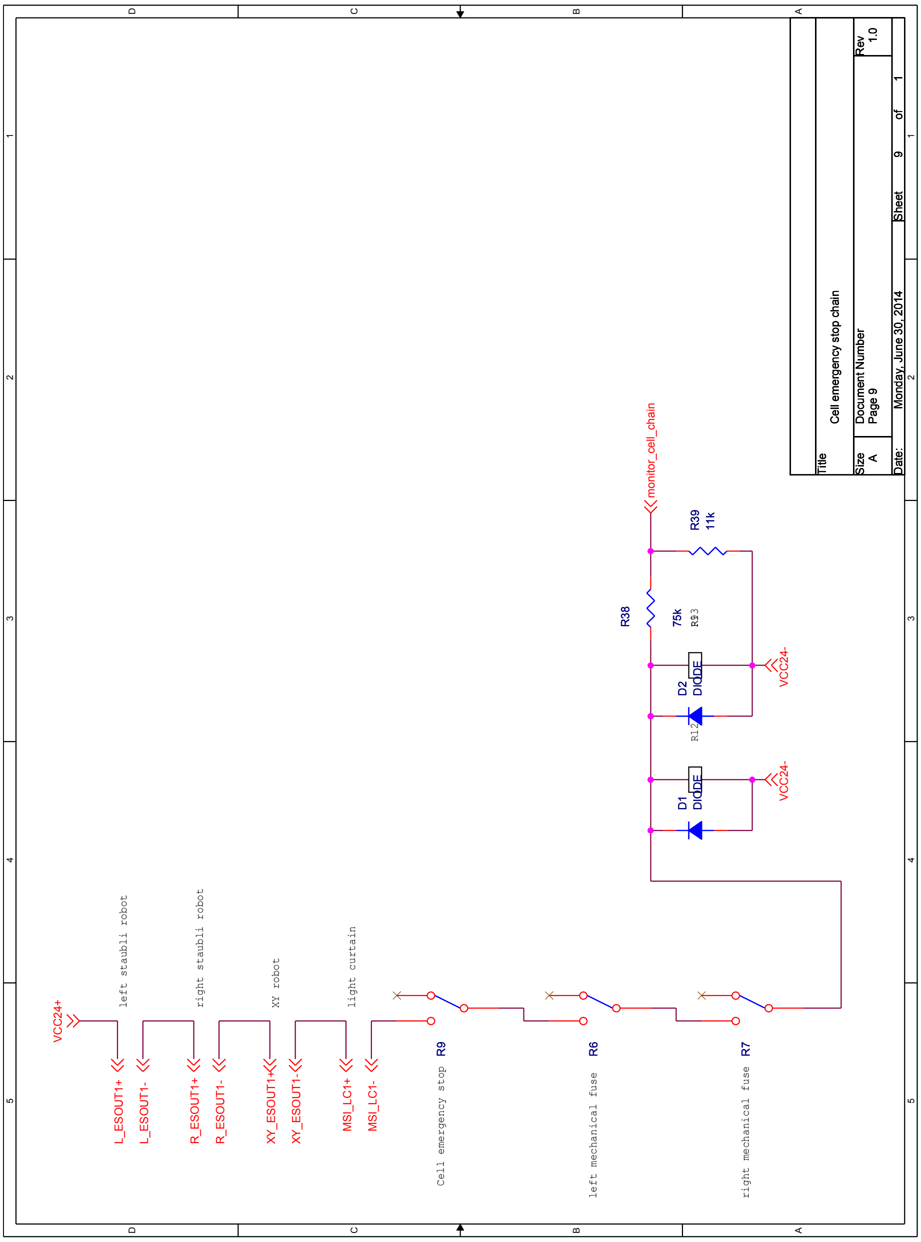
In all the emergency stop chains presented in this section, the outputs of all the required safety features are serially connected, basically implementing a logical AND function. That is, all the safety features must be valid (closed circuit) for the robot to be in operating condition. Only that one of the safety features becomes invalid (the circuit is opened), the corresponding robot will stop working.

The resistive voltage dividers present in each of the emergency stop chains are connected to the dedicated embedded system to monitor the status of all the safety features of the work-cell. See section B.5 and the technical report [7] for more details.

Cell emergency stop chain

As summarized in Table 1 in section 2, the cell emergency stop chain takes into account all the safety features of the work-cell. The safety signals for the left ($L\_ESOUT1+$ and $L\_ESOUT1-$) and right ($R\_ESOUT1+$ and $R\_ESOUT1-$) Staübli robots, the XY robot ($XY\_ESOUT1+$ and $XY\_ESOUT1-$) and the laser curtain (MSI_LC1+ and MSI_LC1+) come directly from the devices themselves.

The other safety features are used through a normally open contact of a relay. See Appendix B.7 for the circuit used to activate the cell emergency stop relay R9 and Appendix B.8 for the circuit used to activate the left and right mechanical fuses relays R6 and R7. The two relays (R12 and R13) that are handled by this emergency stop chain control 4 normally open circuits, which are used for each one of the emergency stop chains of the robots.

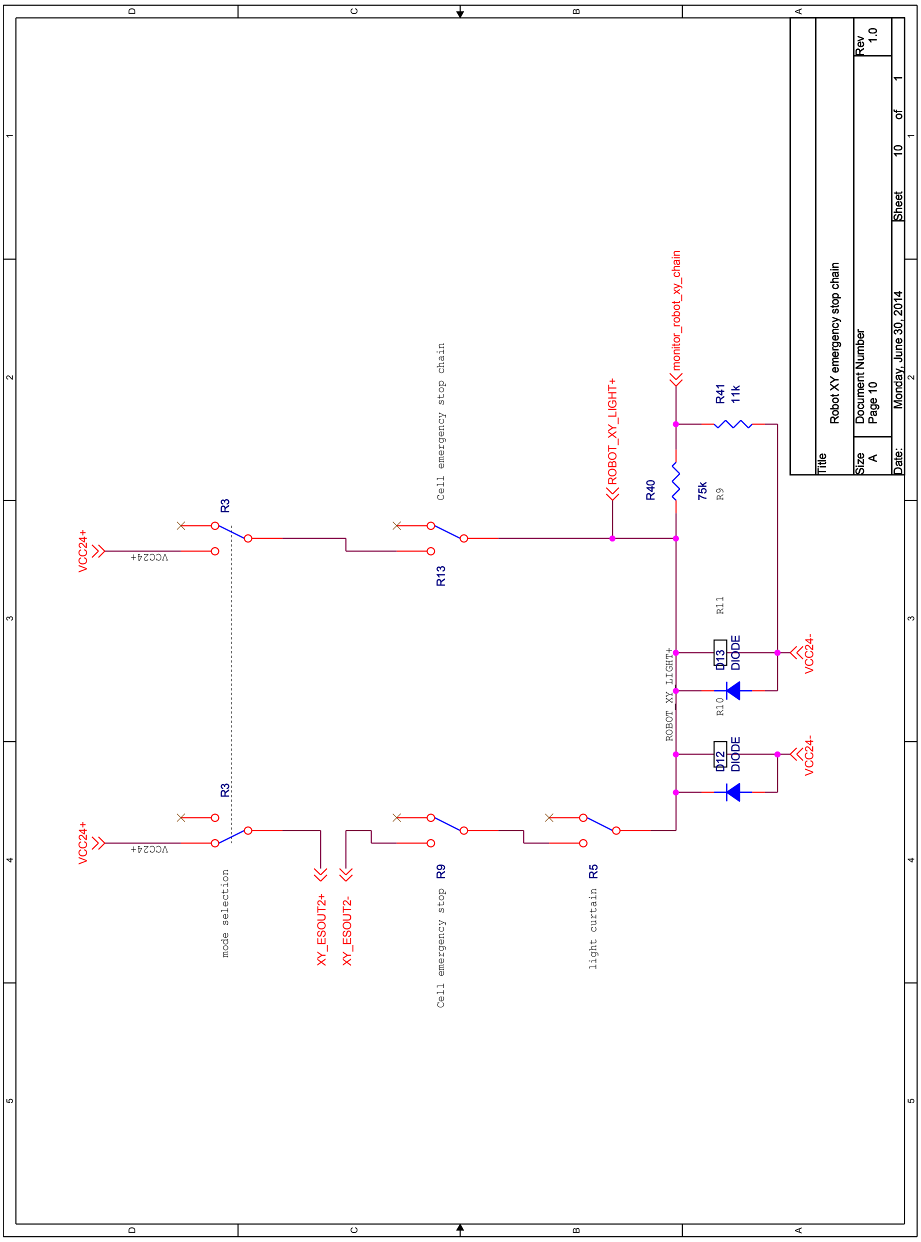


Robot XY emergency stop chain

The left branch of this emergency stop chain is for the independent mode, and the left one for the cell mode. The active chain is chosen by relay R3, controlled by the mode selector in the control pendant (see section 2.6).

The safety signals for the XY robot ($XY\_ESOUT2+$ and $XY\_ESOUT2-$) come directly from the devices themselves. The other safety features are used through a normally open contact of a relay. See Appendix B.7 for the circuit used to activate the cell emergency stop relay R9 and Appendix B.9 for the circuit used to activate the laser curtain relay R5.

The two relays (R10 and R11) that are handled by this emergency stop chain control 4 normally open circuits, which are used to cut power to both motors of the XY robot (see Appendix B.4). The same signal used to control this relay is also used for a visual indicator of the state of the XY robot emergency stop chain in the control pendant (see section 2.6).

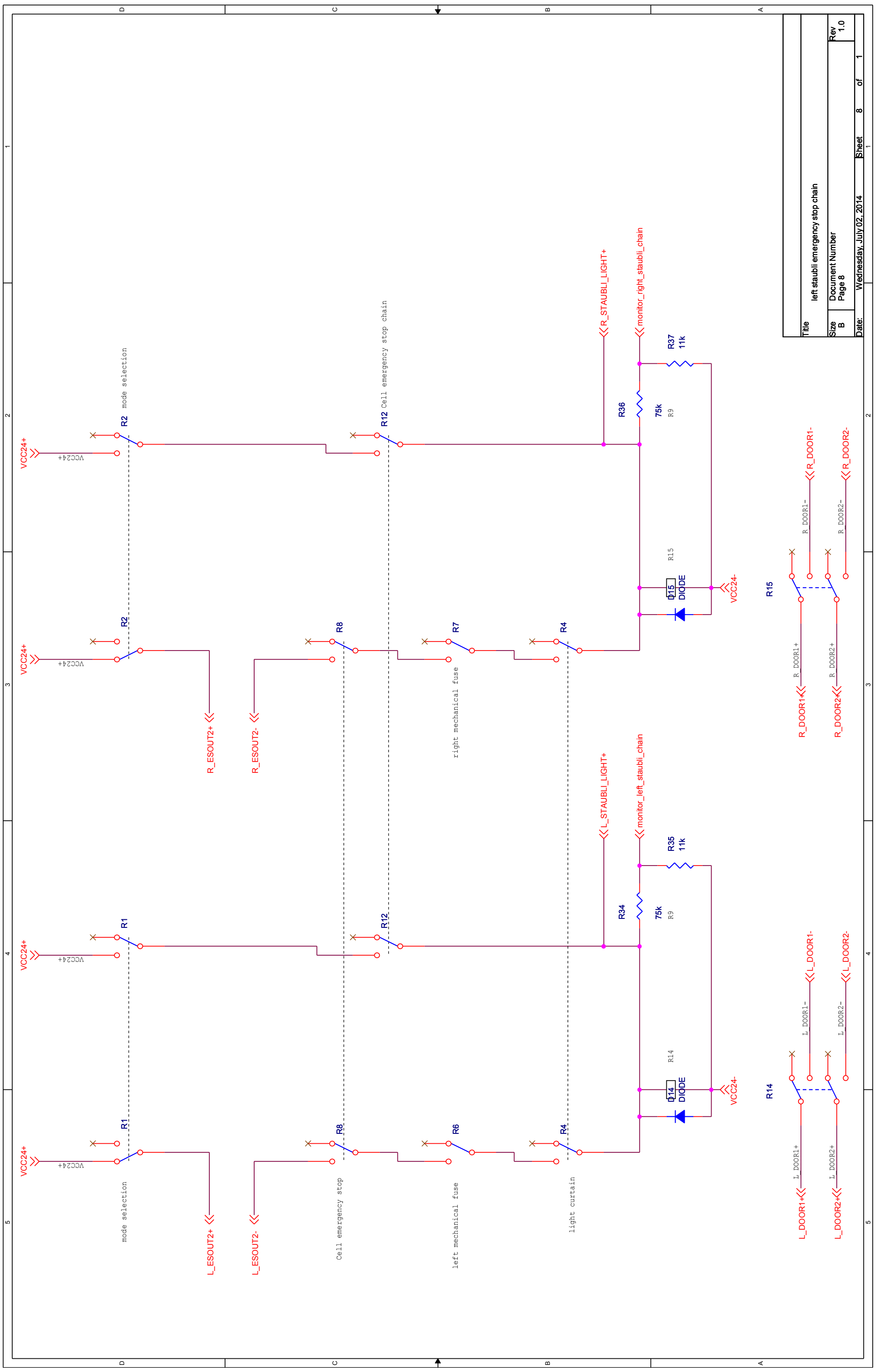


Staübli emergency stop chain

The emergency stop chains for both the left and right Staübli robots are equivalent. The left branch of this emergency stop chain is for the independent mode, and the left one for the cell mode. The active chain is chosen by relays R1 and R2, controlled by the mode selector in the control pendant (see section 2.6).

The safety signals for the corresponding Staübli robot ($L\_ESOUT2+$ and $L\_ESOUT2-$ or $R\_ESOUT2+$ and $R\_ESOUT2-$) come directly from the robots themselves. The other safety features are used through a normally open contact of a relay. See Appendix B.7 for the circuit used to activate the cell emergency stop relay R8, Appendix B.8 for the circuit used to activate the left and right mechanical fuses relays R6 and R7 and Appendix B.9 for the circuit used to activate the laser curtain relay R4.

The two relays (R14 and R15) that are handled by this emergency stop chain control 4 normally open circuits, which are used for the left and right external emergency stop input of the Staülbi robots (L_DOOR1, L_DOOR2, R_DOOR1 and L_DOOR2). The same signals used to control these relays are used for a visual indicator of the state of each of the Staübli robots emergency stop chains in the control pendant (see section 2.6).


VCC24+
R_ESOUT2+
R_ESOUT2-
L_ESOUT2+
L_ESOUT2-
R_STAUBLI_LIGHT+
monitor_right_staubli_chain
L_STAUBLI_LIGHT+
monitor_left_staubli_chain
R36
75k
R37
11k
R34
75k
R35
11k
D15
DIODE
D14
DIODE
VCC24-
R15
R14
R_DOOR1+
R_DOOR1-
R_DOOR2+
R_DOOR2-
L_DOOR1+
L_DOOR1-
L_DOOR2+
L_DOOR2-
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A Appendix: Box connectors

Fig. 16 shows a sketch of the side of the control box where all the external connectors are placed. The grayed slots are currently free and can be used for future upgrades.

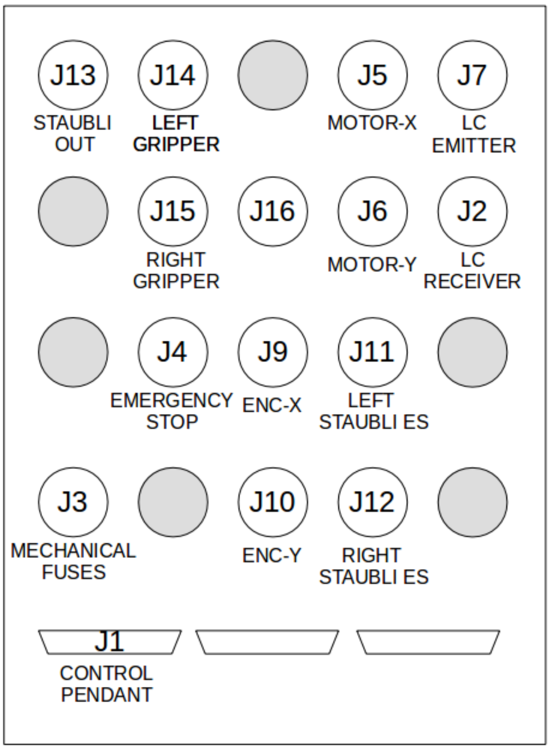


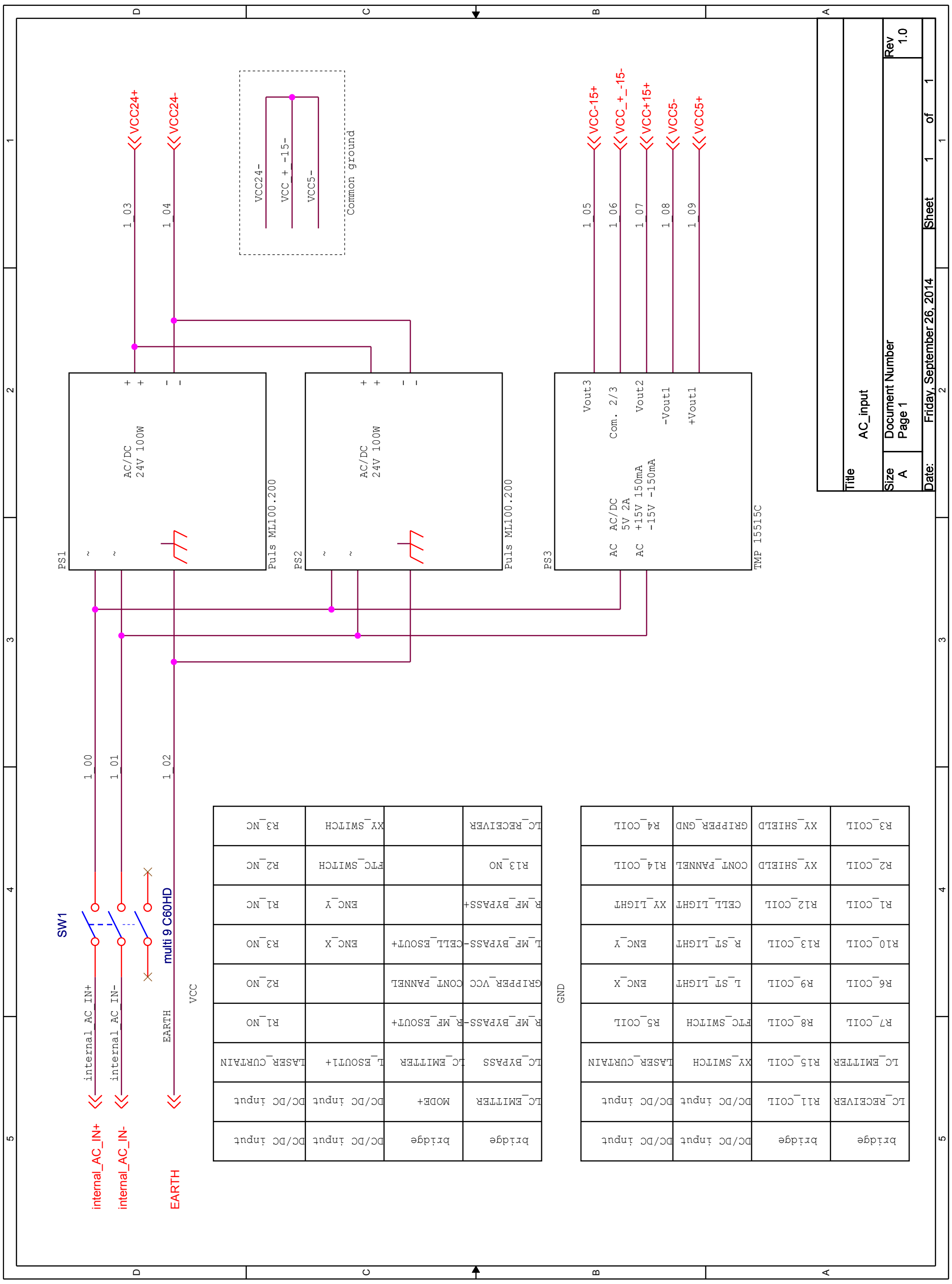
Figure 16: Sketch of the connectors of the control box viewed from the outside.

B Appendix: Electric diagrams

The information and electric diagrams provided in this Appendix are intended to be used for maintenance and as a reference for future upgrades.

B.1 AC input

Two Puls ML100.200 24V power supplies work in tandem to provide enough power to the whole system, and the TMP 15515C power supply is only used for the embedded system. The two tables show the power and ground connections for each of the devices as seen on the control box.



VCC:

bridge	bridge	DC/DC input	DC/DC input
LC_EMITTER	MODE+	DC/DC input	DC/DC input
LC_BYPASS	LC_EMITTER	L_ESOUT1+	LASER_CURTAIN
R_MF_BYPASS-	R_MF_ESOUT+		R1_NO
GRIPPER_VCC	CONT_PANNEL		R2_NO
L_MF_BYPASS-	CELL_ESOUT+	ENC_X	R3_NO
R_MF_BYPASS+		ENC_Y	R1_NC
R13_NO		FTC_SWITCH	R2_NC
LC_RECEIVER		XY_SWITCH	R3_NC

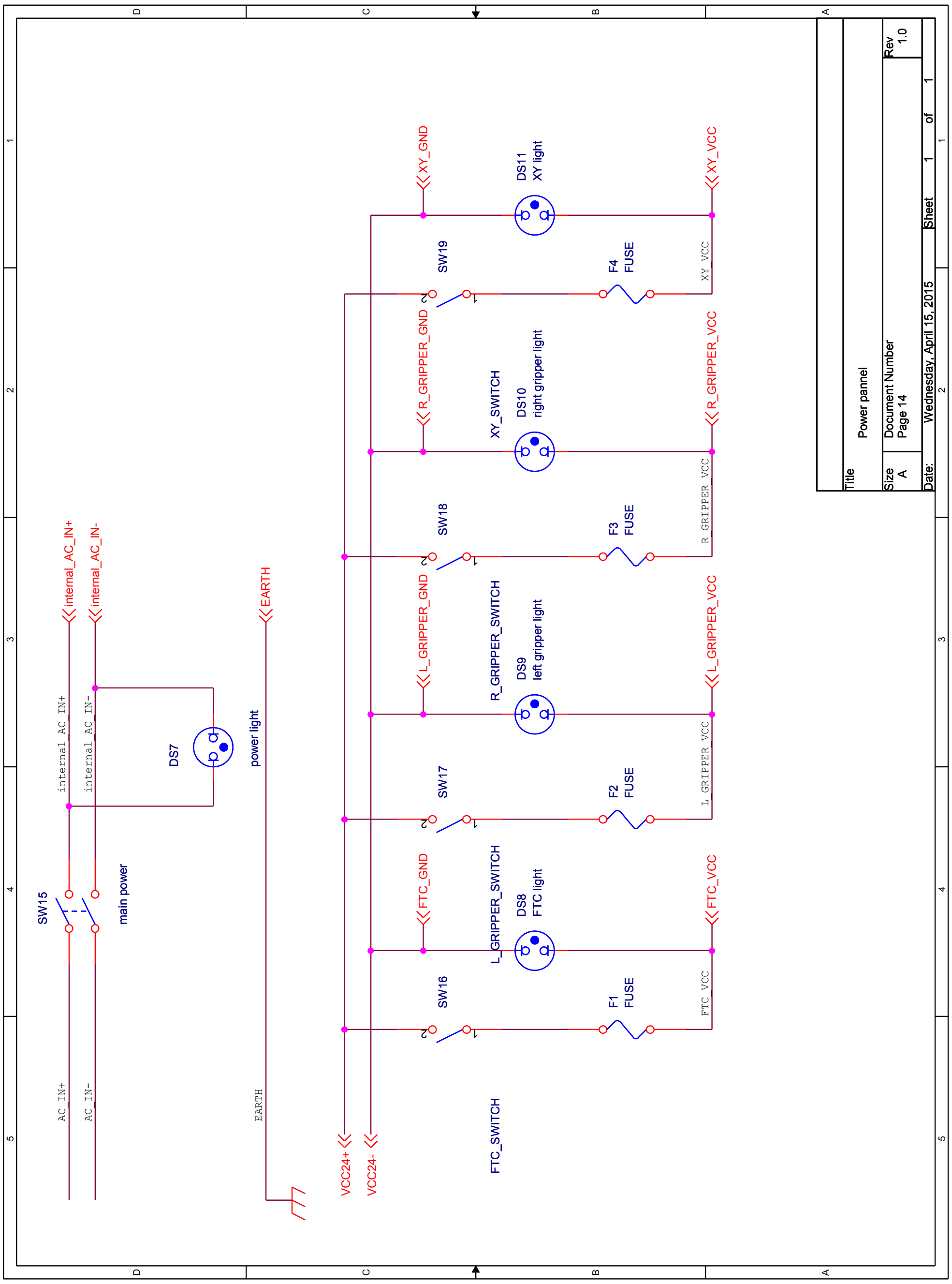
GND:

bridge	bridge	DC/DC input	DC/DC input
LC_RECEIVER	R11_COIL	DC/DC input	DC/DC input
LC_EMITTER	R15_COIL	XY_SWITCH	LASER_CURTAIN
R7_COIL	R8_COIL	FTC_SWITCH	R5_COIL
R6_COIL	R9_COIL	L_ST_LIGHT	ENC_X
R10_COIL	R13_COIL	R_ST_LIGHT	ENC_Y
R1_COIL	R12_COIL	CELL_LIGHT	XY_LIGHT
R2_COIL	XY_SHIELD	CONT_PANNEL	R14_COIL
R3_COIL	XY_SHIELD	GRIPPER_GND	R4_COIL

B.2 Power panel

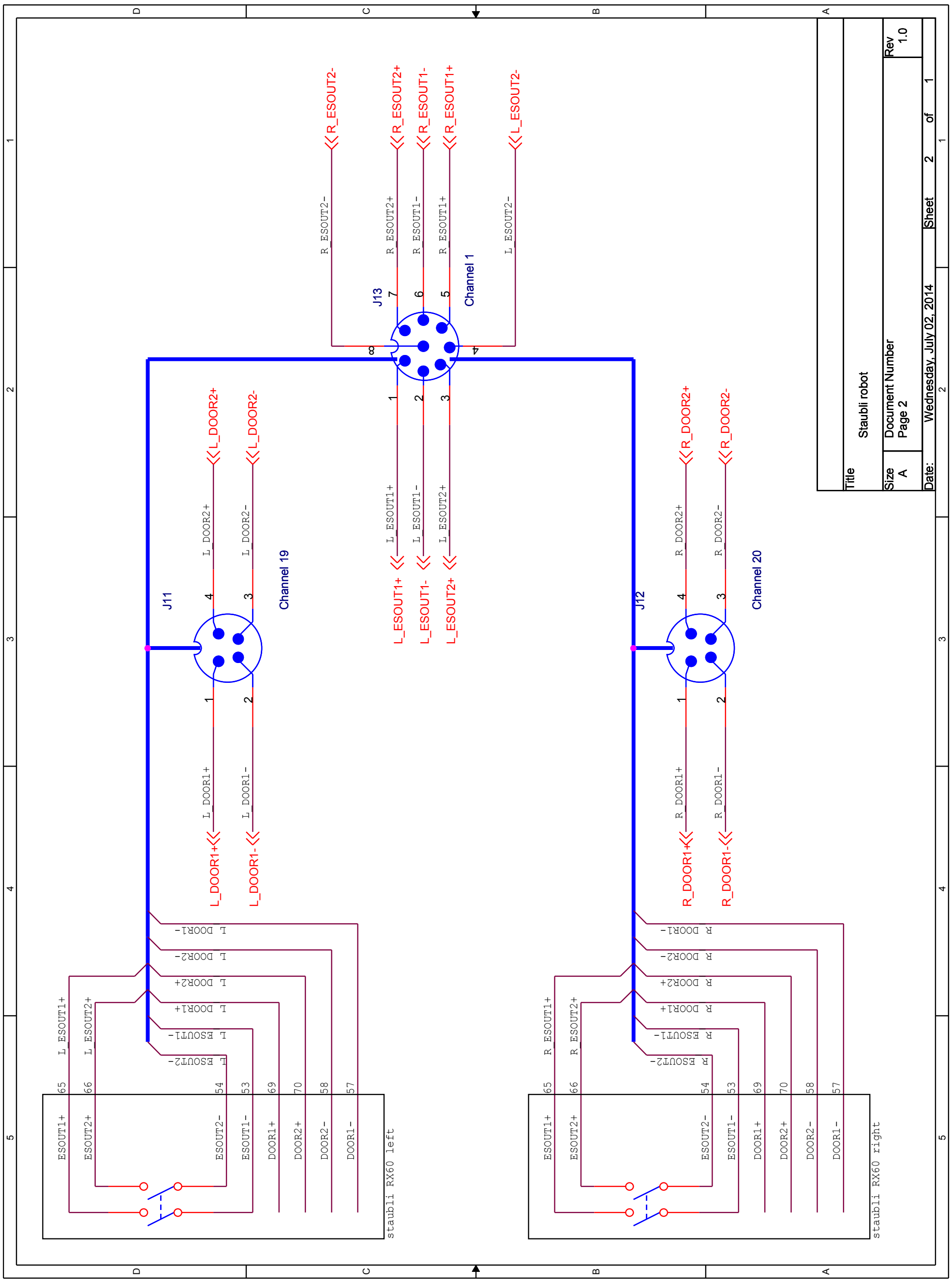
The power panel at the lower left corner of the front side of the Staübli work-cell has a main AC power switch to provide power to the safety features and to the internal DC power supplies shown in Appendix B.1. Other power switches are provided to control power to the XY robot, to the force and torque sensor and to both grippers.

Each power switch has a light indicator associated to it to show its current state. A red light ($DS7$) is used for the main power and green lights are used for the other power lines ($DS8$ to $DS11$). Also, a fuse is present in these other power lines to prevent additional protection against power surges. These fuses are properly labeled in the control box in case a fuse needs to be replaced.



B.3 Staübli robots

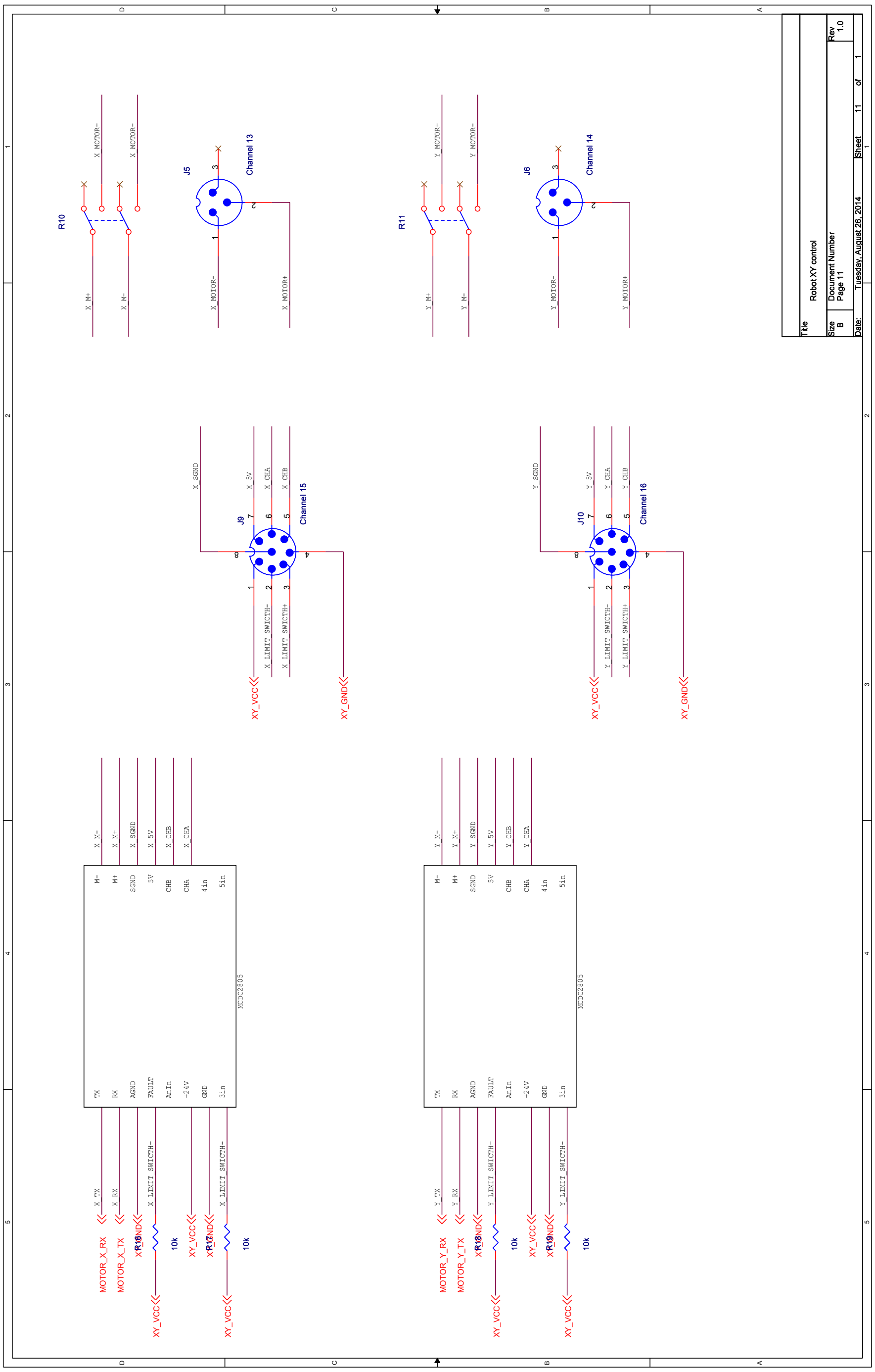
The emergency stop inputs for each Staübli robot use a separate connector (J19 for the left Staübli robot on J12 for the right one). The emergency stop outputs of both robots use a single connector (J13). See section A for the position of these connectors in the control box.



B.4 XY robot

The two motor controllers for each of the axis of the XY robot are inside the control box. Two connectors are used for each axis: one for the motor power lines (J5 for the X axis and J6 for the Y axis), and another one for the data signals, both encoders and motion limit switches (J9 for the X axis and J10 for the Y axis). The cables used to carry the encoder and motion limit switches are shielded to reduce as much as possible interferences from other elements of the work cell. See section A for the position of these connectors in the control box.

This diagram also shows the relay circuits used to halt the normal operation of the XY robot. These relays are controlled by the emergency stop chain presented in section 3.6. The two serial interfaces required to control each of the axis of the XY robot are internally routed to the embedded system (see the technical report [7] for detailed description of this system).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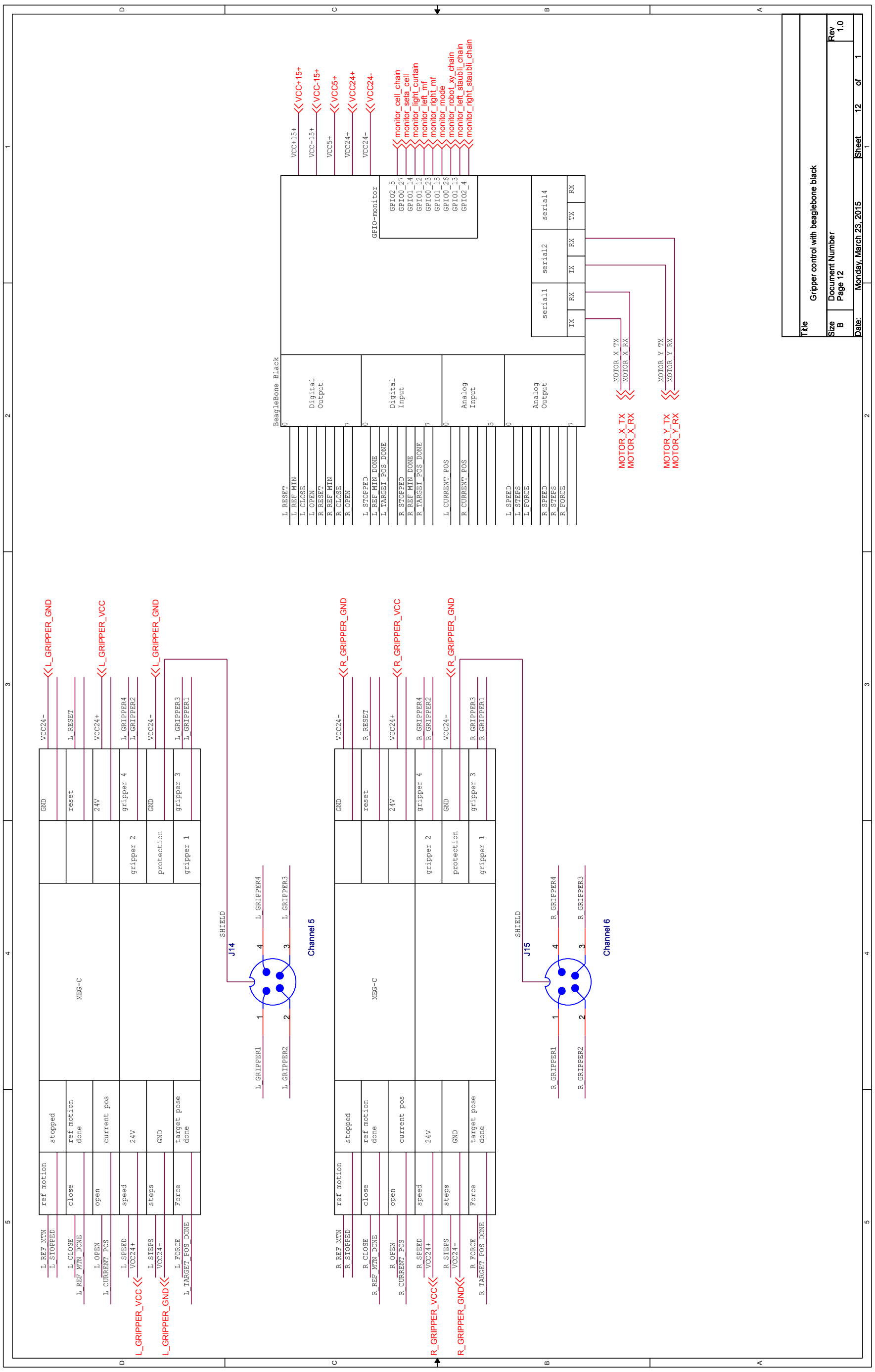
Channel 13
Channel 14
Channel 15
Channel 16
MCDC2805
MCDC2805
MOTOR_X_RX
MOTOR_X_TX
MOTOR_Y_RX
MOTOR_Y_TX
XY_VCC
XY_GND
10k

B.5 MEG50EC grippers

The two controllers of the gripper are inside the control box. A single connector is used for the output control signals of each gripper (J14 for the left gripper and J15 for the right one). See section A for the position of these connectors in the control box. To actually reach the grippers, these signals are first connected to the base of the corresponding Staübli robot, as presented in section 2.1. Then, they are routed internally to the forearm of the robot, and from there to the gripper connector. The cables used to carry the grippers control signals are shielded to minimize as mush as possible interferences to other elements of the work-cell.

As presented in section 2.3, each gripper controller requires several analog outputs (for the desired position, speed and force of the jaws), one analog input (for the current position of the jaws), and several digital inputs and outputs for the control and status signals. All these analog and digital signals for both grippers are handled by a dedicated embedded system specifically designed for this task (see the technical report [7] for detailed description of this system).

This embedded system also handles the serial communication to the two robot XY motor controllers, the serial interface to get data from the force and torque sensor, and it also monitors the state of each of the safety features of the work-cell and the current status of the emergency stop chains of both Staübli robots, the XY robot and the whole cell. The different power supply requirements of the embedded system ($\pm 15\,V$ and $5\,V$) are generated by a dedicated DC/DC converter shown in section B.1.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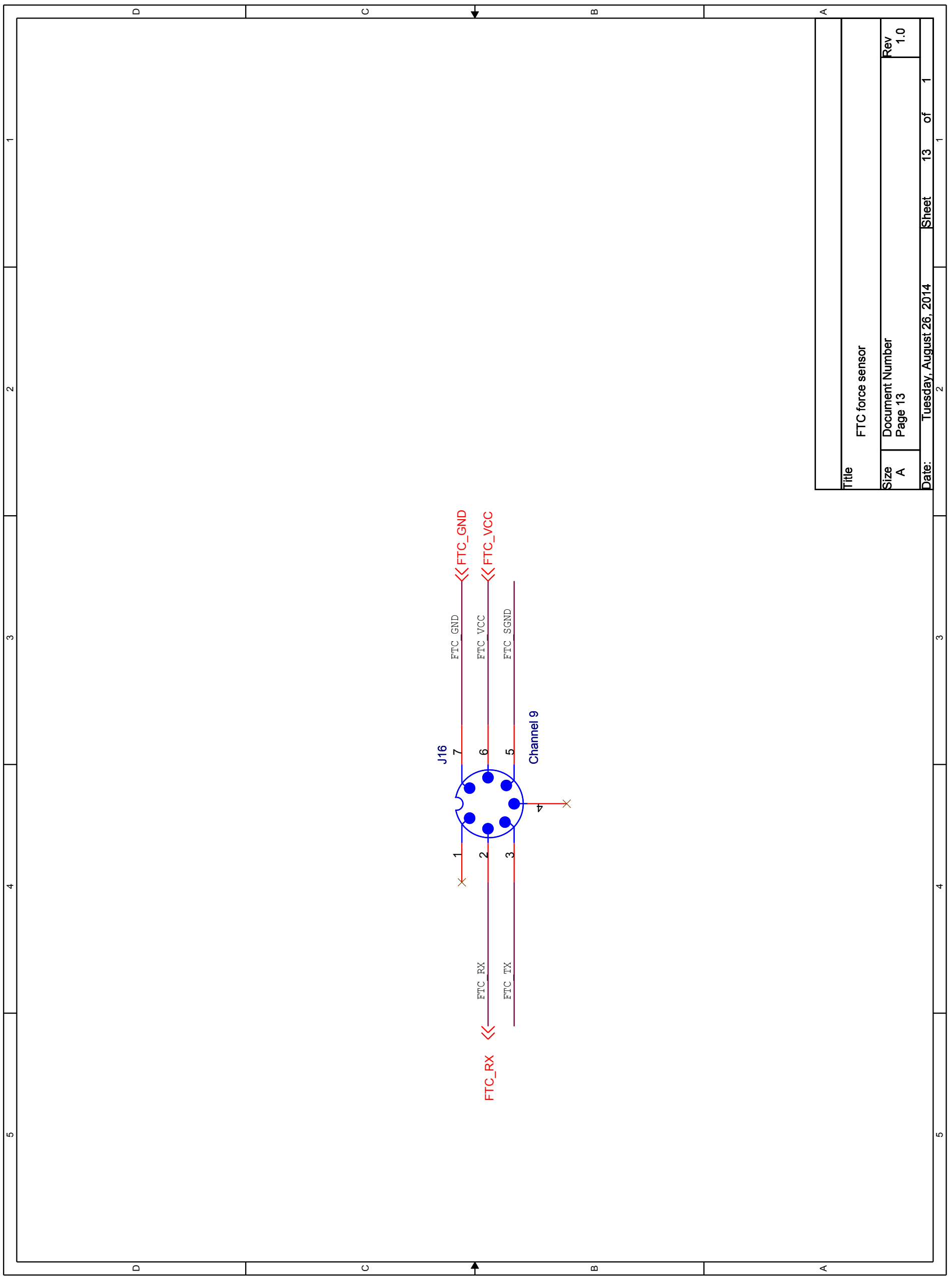
J14
J15
MEG-C
BeagleBone Black

B.6 Force and torque sensor

All the power and signal lines required by the force and torque sensor use a single connector(J16) to access the control box. See section A for the position of this connector in the control box. To actually reach the sensor, these signals are first connected to the base of the corresponding Staübli robot, as presented in section 2.1. Then, they are routed internally to the forearm of the robot, and from there to the sensor connector. The cables used to carry the sensor control signals are shielded to minimize as much as possible interferences from other elements of the work-cell.

One of the serial ports provided by the embedded computer is used to handle the force and torque sensor. See section B.5 and the technical report [7] for more details.

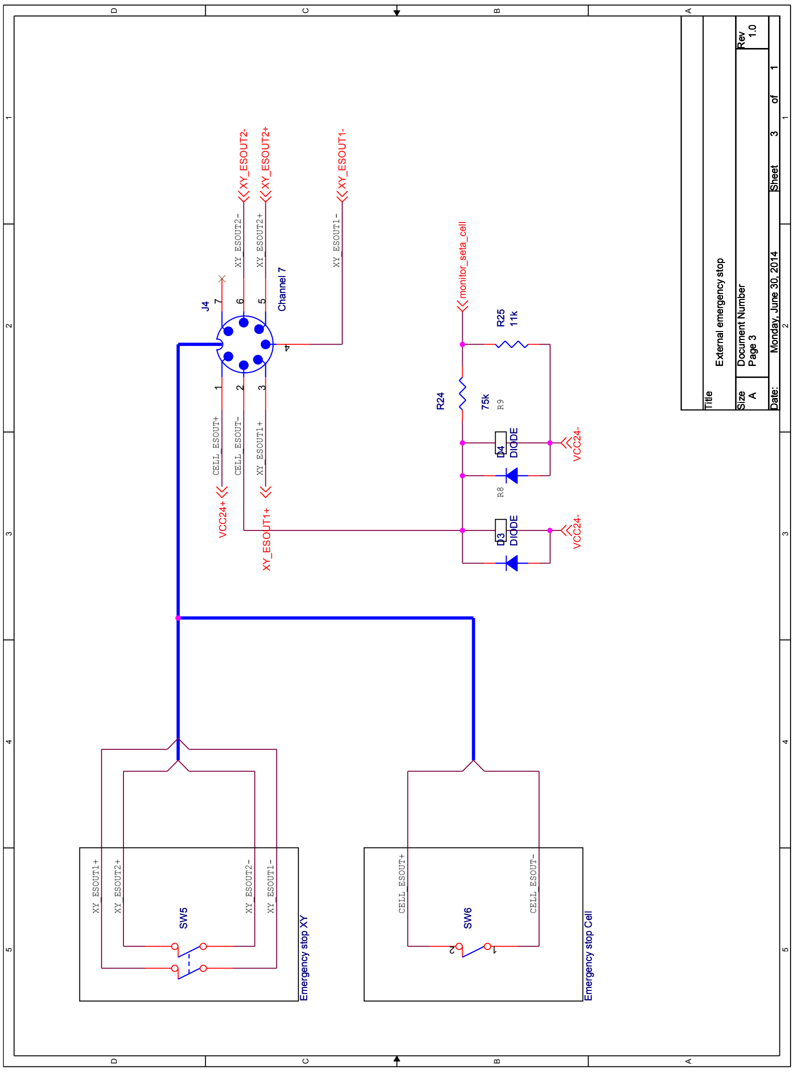


B.7 Emergency stop buttons

A part from the emergency stop buttons integrated into the control pendants of both Staübli robots, the work-cell provides two more emergency stop buttons: one dedicated to the XY robot an the other one dedicated to the whole cell. The emergency stop button for the XY robot has two normally closed circuits, one for the XY robot emergency stop chain and the other one for the whole cell emergency stop chain.

The other emergency stop button provides a single normally closed circuit for the whole cell emergency stop chain. See section 3.6 for detailed information of the emergency stop chains available. All the external emergency stop buttons access the control box through the J4 connector. See section A for the position of this connector in the control box.

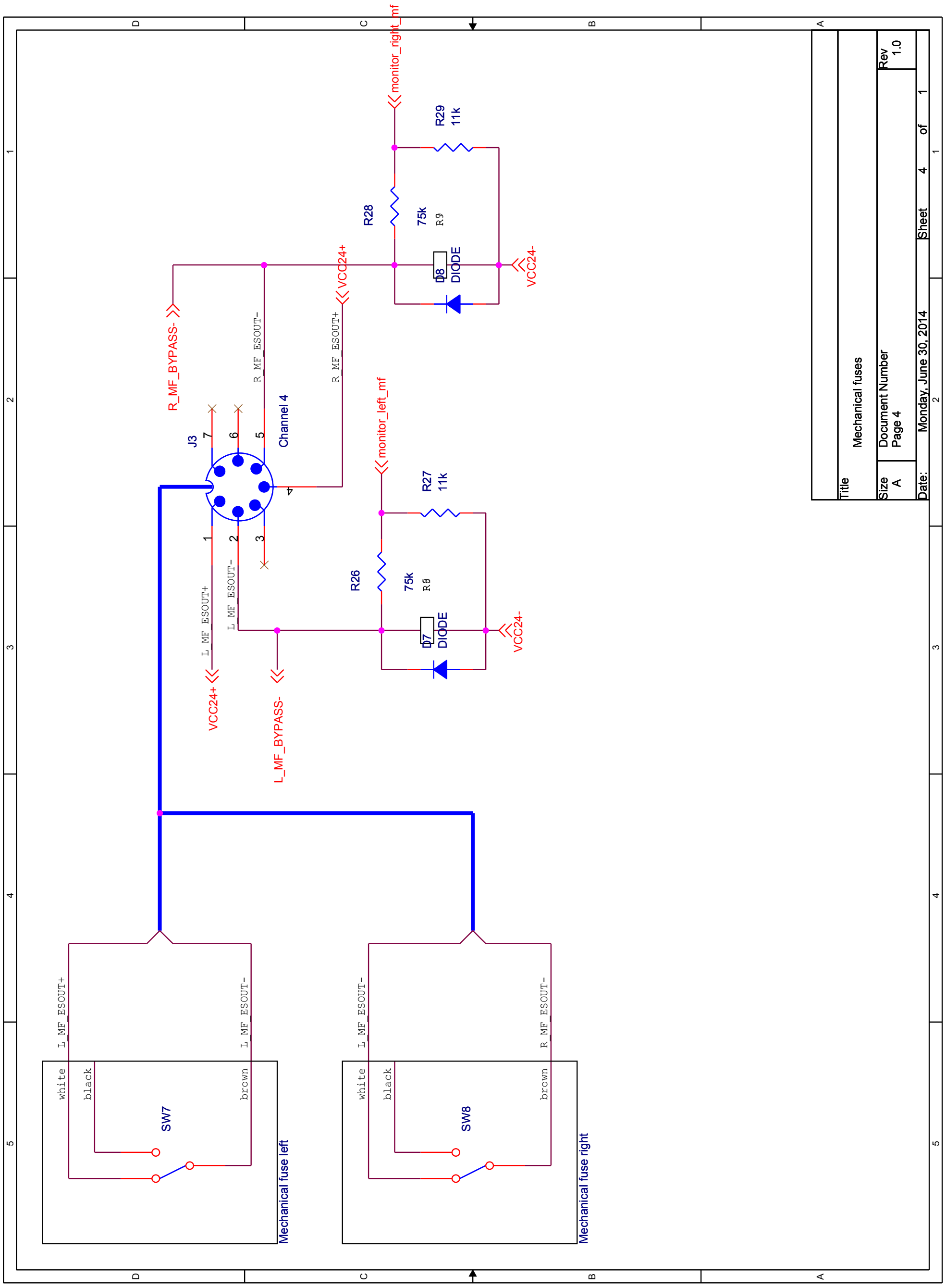
The resistive voltage divider at the $CELL\_ESOUT-$ signal is connected to the dedicated embedded system to monitor the status of all the safety features of the work-cell. See section B.5 and the technical report [7] for more details.



B.8 Mechanical fuses

The two mechanical fuses use the same connector (J3) to access the control box. See section A for the position of this connector in the control box. The resistive voltage dividers at the L_MF_ESOUT- and R_MF_ESOUT- signals are connected to the dedicated embedded system to monitor the status of all the safety features of the work-cell. See section B.5 and the technical report [7] for more details.

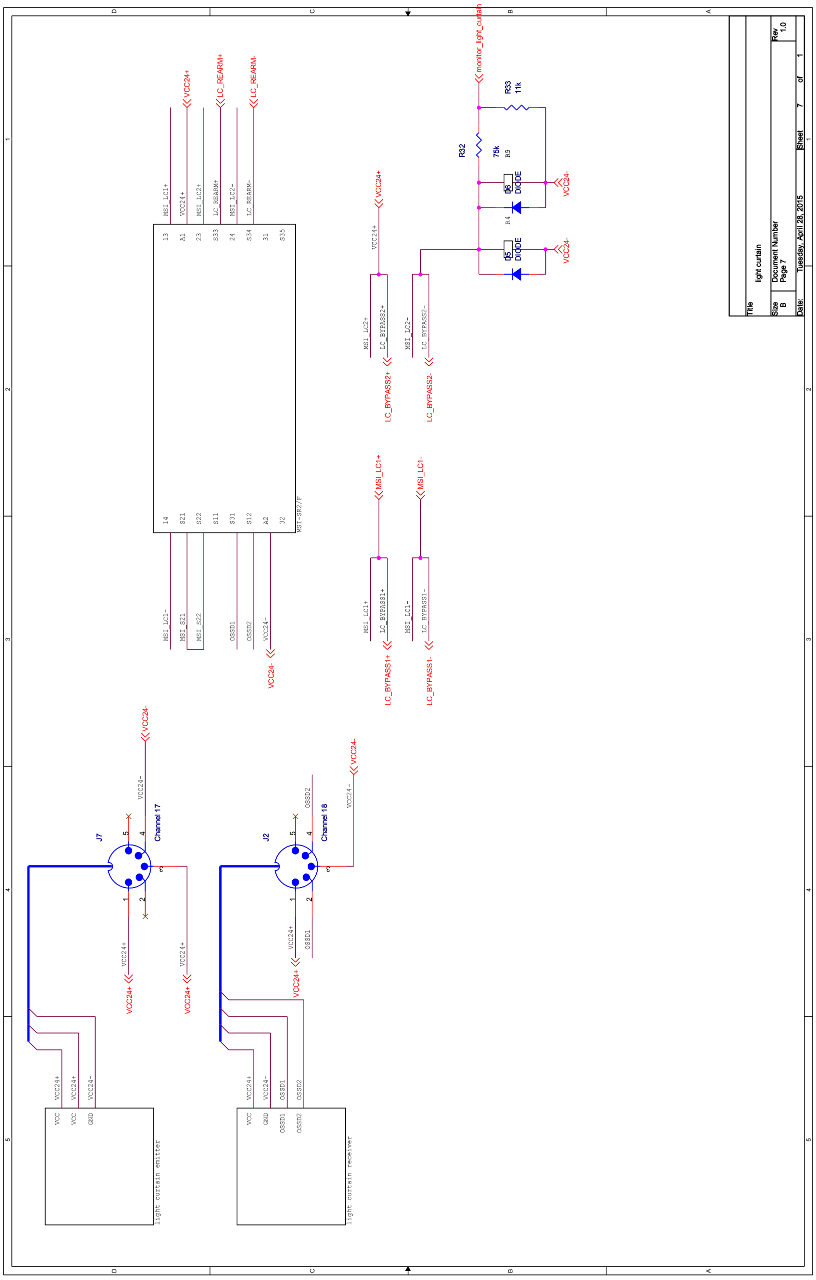
The normal operation of the mechanical fuses can by by-passed, when they are not required, by using two dedicated selectors in the control pendant ($L\_MF\_BYPASS-$ and $L\_MF\_BYPASS-$ signals), one for each mechanical fuse (see section 3.3 for more details).



B.9 Laser curtain

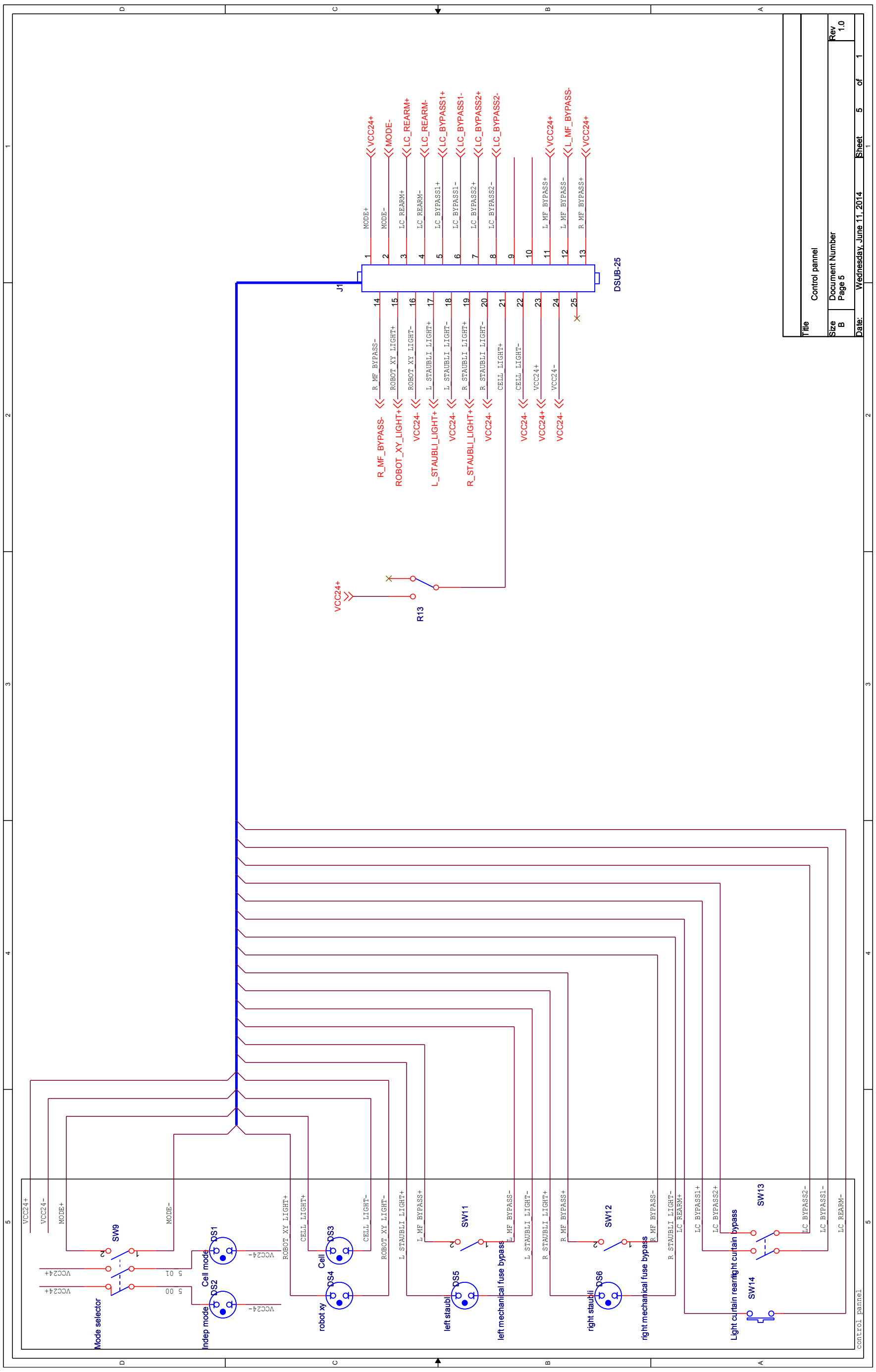
The laser curtain transmitter uses the connector J14 to access the control box, and the receiver uses the connector J2. See section A for the position of these connectors in the control box. The resistive voltage divider at the MSI_LC2- signal is connected to the dedicated embedded system to monitor the status of all the safety features of the work-cell. See section B.5 and the technical report [7] for more details.

The normal operation of the laser curtain can by by-passed, when it is not required, by using a dedicated selector in the control pendant ($LC\_BYPASS1$ and $LC\_BYPASS2$ signals). See section 3.4 for more details.



B.10 Control pendant

All the status and control signals required by the control pendant use a single DB25 connector (J1) to access the control box. See section A for the position of these connectors in the control box.



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