Fakultät für Informatik

Bachelorarbeit in Informatik

Concept and assembly of a closed loop for contrast regulated laser marking of objects using a sensor guided robot with a two axes deflection unit

Benjamin Brandenbourger

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Concept and assembly of a closed loop for contrast regulated laser marking of objects using a sensor guided robot with a two axes deflection unit

Entwurf und Aufbau eines Regelkreises zur kontrastgeregelten Laserbeschriftung von Gegenständen unter Verwendung eines sensorgestützten Roboters mit 2-Achsablenkeinheit

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I assure the single handed composition of this bachelor's thesis and that it is supported only by declared resources.

Ort, Datum

Unterschrift

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1. Acknowledgments

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Furthermore, I would like to thank the OPP2 team, who willingly provided information at any time.

2. Introduction

MBDA (Matra BAe Dynamics), a world leading missile manufacturer, is a multi-national group with 9,900 employees in France, Germany, Italy and Britain. MBDA had an annual turnover of 3 billion Euros in 2007 by producing over 3,000 missiles and achieving an order book of 13.1 billion Euros. After the amalgamation of the main missile producers in France, Italy and Great Britain, MBDA was created in December 2001. Five years later, the German affiliated company EADS/LFK was acquisitioned.

Meanwhile, MBDA offers a series of 45 products in service like MILAN, an anti-armour weapon which has been supplied to over 40 nations in the world or TRIGAT LR, a third-generation anti-tank missile for long-range applications. This missile is better known as PARS-3 (Panzerabwehr Raketensystem 3) in Germany or as AC 3G (AntiChar de 3e Génération) in France.[1]

For better transportation, the missile is preserved in a launch tube which is labeled with different signs. Up to now, a strickle was placed on the launch tube and painted over with white color. The inconveniences with this method were the color, which sometimes ran under the foil, the long drying time, and the fact that the process had to be done manually. Thus it was suggested that the marking of the launch tube be done with an automatic laser system.

[1] MBDA Homepage

3. Purpose statement

The goal of the bachelor's thesis is to develop automatic laser engraving equipment for the PARS-3 LR project which consists of a robot, a laser system, a camera and a graphic user interface (GUI). A camera system is used to check the engraving quality.

Following tasks should be fulfilled within the scope of this thesis:

- Designing a concept for assembly and coaction of the individual components (robot, camera, laser, GUI)
- Definition of the electrical interfaces between the components
- Creating an application program including a GUI with LabVIEW
  - Automatic start and quality control of the inscription
- creating a safety concept embedded in the laser cabin
- Creating a run capable complete system

Circumstances permitting, the following increments are conceivable and desirable:

- complete engraving of the PARS launch tube with all final symbols
- choosing different parts to be engraved (e.g. PARS missile)
- Menu for free marking of type plates etc.

4. Requirements

In order to fulfil the tasks mentioned above, several requirements need to be met. First of all, the launch tube needs to be covered with three different layers of paint: the first layer is a grounding to protect the metal from corrosion. The second layer is a white or yellow colour which will be seen after the engraving process (see 5.1.Basic principles of laser engraving) and the third layer is a camouflage cover. As the launch tube is lacquered by hand, it is logical that some irregularities can appear. Therefore, the second requirement is a uniform coat of each layer and a thickness of 25µm in order to obtain the best engraving results. Other thicknesses would also work but the laser beam would have to be readjusted to the given circumstances (see 7.3.10.Test series).

Another requirement to the system is a well-defined distance between the robot and the turnover positioner (see 5.2.Build-up of the complete system) as the system should have the possibility to be removed and set up at another place. This can be achieved by placing each the robot and the turnover positioner on an iron plate and fixing two bars between the plates. Placing the robot and the turnover positioner on the same plate would lead to one oversized and too heavy iron plate which could hardly be moved.

The distance between the laser and the launch tube needs to also be constant, otherwise the marking process would lead to insufficient paint ablation or irreversible damages to the grounding. These problems can be prevented by using a distance indicator or by referring to the repeat accuracy of the KUKA robots of 1/10 mm.

The last requirement relates to the illumination. As the camera system works with histograms and thresholds, variant illuminating can lead to different checking results. Thus, the system needs to be placed in a cabin with well-defined luminous sources.

5. Technical Implementation

As the automatic laser engraving equipment shall also be used to mark type plates or other parts of missiles, high application flexibility is required. Hence a robot with six degrees of freedom and one additional seventh rotatory axis is used. In order to accomplish the main task of marking the launch tube, in principle two axes would be sufficient (one rotatory axis for the rotation and one linear axis to move along the tube). However, this setup would be too inflexible.

The engraving process can be accomplished with two different methods: The first method would be the employment of a milling cutter which has the disadvantage of having to swap the tools depending on how strong a line should be. Furthermore, the milling cutter must be precisely moved over the cylindrical launch tube to obtain good results, which is a big challenge considering the play of maximum 10 µm in the second layer of paint. For this reason, the engraving is carried out by the second method, a pulsed laser, which doesn't need any tool-swap, which can be configured with different energies for different engraving results, and which is able to engrave in an interval of ± 9mm around the focal distance, allowing the curvature of the tube to be disregarded in a small field (see Figure 28).

In order to create a reliable checking process, a camera system is most efficiently employed. After running several test series, thresholds came up which determined good or bad engraving results.

The decision for LabVIEW as GUI can be ascribed to the fact that MBDA develops lots of test devices controlled in this visual programming language. For better understanding and easier traceability, an implementation of the GUI in Visual Basic was dismissed in the early planning phase.

5.1.Basic principles of laser engraving[2]

Laser engraving is the inscription or marking of objects by means of a strong laser beam. Contrary to the laser printing where a weak laser beam controls the application of pigments on the material to be printed, the laser engraving directly alters the surface of the material. The kind of laser marking and the amount of energy to be used depends, therefore, strongly on the material of the surface.

Laser inscriptions are waterproof, wiping resistant and durable. They can be realized fast, automatically and individually, thus the technique is often used to number component parts. Depending on the material, several effects can be achieved with the laser engraving, such as colouring.

As mentioned before, there are different kinds of laser marking. For example, in organic materials like paper, wood or leather the local heating leads to chemical conversion reactions which can be observed as a colour change. This reaction is comparable to branding. The effect can also be seen on special organic plastics that show a specific colour change by heating. This possibility expands the spectrum of attainable colour alternatives.

Paint ablation can also be purposefully done using a paint ablation on multiple coated objects. This ablation allows a deeper layer of colour to emerge. This method has

[2] Concept laser engraving

been used since the end of the 1980's in automotive engineering to label illuminated control elements.

Due to oxidative processes, a colour coat can be observed on metallic surfaces when heated up to a certain temperature. Relating to steel, it's known as blueing. The colour coat, depending on the temperature, can be noticed on chromed tail pipes of motorcycles as well.

The energy of the laser can also be used for material removal so that an engraving appears on the surface. However, the engraving does not necessarily involve a colour change, so it's usually less apparent. On the other hand, it is more durable, as it can only be removed by deep abrasion.

The last method of laser marking is the inside-engraving of clear-transparent materials such as acrylic glass or normal glass. Hereunto the laser's focus is placed in the material with temperatures of up to 20.000°C, which results in a durable, intransparent spot. Hence three-dimensional figures can be engraved by moving the laser's focus.

For engraving the launch tube, the method of paint ablation is used because the tube needs to be coated anyway with a grounding and camouflage cover. Moreover, the best readability of the signs comes out of the paint ablation method, provided that the second and the top layer of colour are rich in contrast.

Finally, the engraving mode needs to be chosen. One mode is Marking On The Fly (MOTF) where the launch tube is rotated while the laser is working. The robot can also move the laser along the tube so that bigger inscriptions can be marked at once. This mode is not recommendable, as the robot's movement have acceleration and brake phases that would lead to irregular engraving intensity. Much better is the progressive marking mode. In this mode, the robot moves in a specific configuration and holds the position until the marking process is finished. Uniformity and sharpness are the advantages; a disadvantage is the restriction of the maximal figures size to 18 * 18 cm^2 due to the lens (see 7.3.6.F-Theta-lens). On the basis of the robot accuracy, bigger figures can be split in several engraving-jobs that can be accomplished consecutively.

5.2.Build-up of the complete system

The system's components need to be arranged in a cabin that meets certain criteria. First of all, the robot needs an operating range that allows for each engraving position on the launch tube and the turnover positioner to be placed for easy access so that the launch tubes can be changed. Furthermore, the cabin should have no window to ensure well-defined luminous sources. If necessary, the operator can observe the engraving process on a screen, fixed on the outside of the cabin, which shows the robot and the launch tube through a camera on the inside. If an insistence on a window arises, it should be noted that a window with laser-beam-absorbing covering should be used to protect persons standing outside. Because the cabin is closed during the engraving process, emerging vapours from the burnt paint should be extracted by an exhaust hood.

As for the security, a safety-switch at the door guarantees an immediate switch-off of the laser and robot to prevent harm to inattentive persons. Additionally, an emergency-off button on the inside and outside can switch off the complete system. Furthermore, a warning light fixed on the outside of the room indicates the online state of the laser. Finally, the operator has a touch panel with additional hardware buttons positioned nearby which shows the GUI. The hardware buttons are required for example to confirm that the operator is outside the room or to enable motion after the robot has crashed.

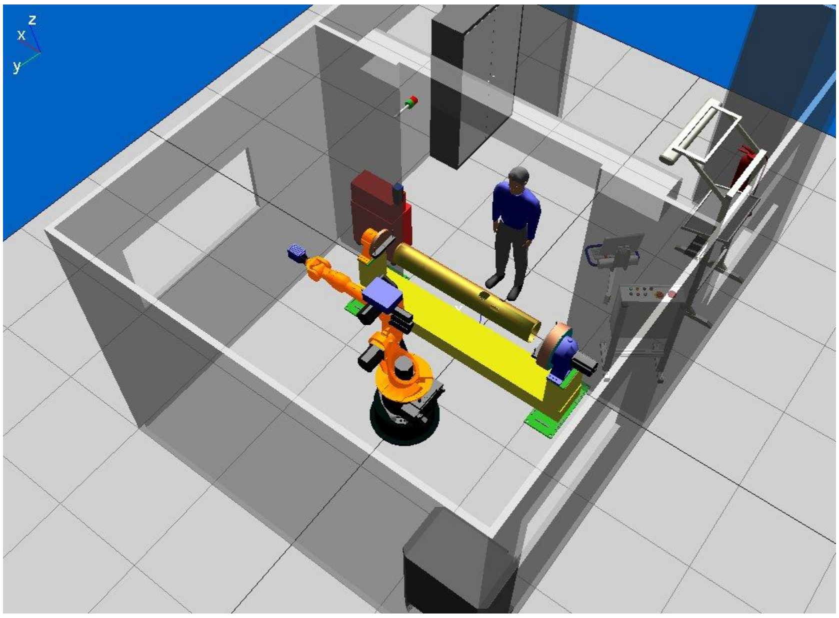


Figure 1: Robot cabin

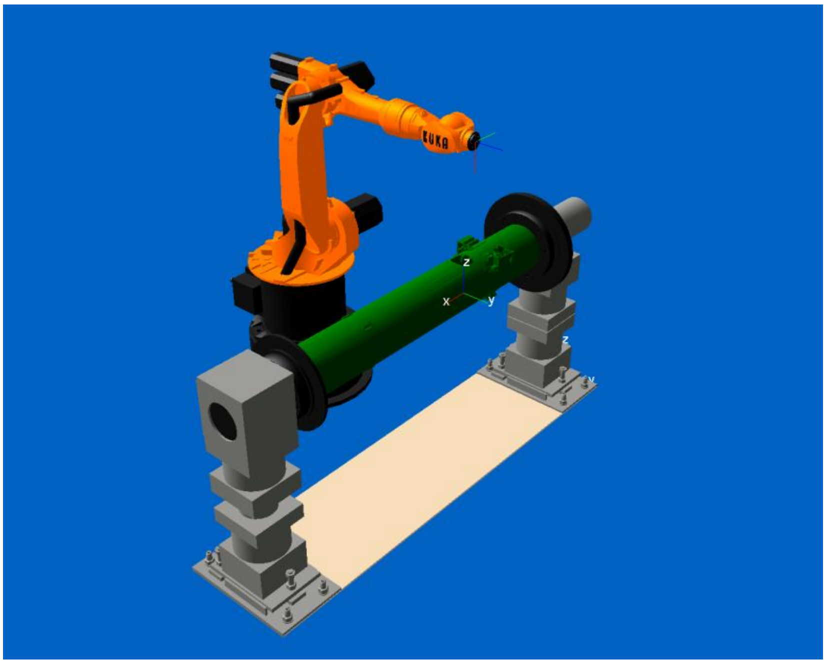


Figure 2: Robot with turnover positioner

6. Concepts

After the technical implementation has been clarified, the appropriate concept needs to be worked out. In each concept, the system's intelligence is located in different components and entails different advantages or disadvantages and the use of different interfaces between the components.

6.1.Robot control

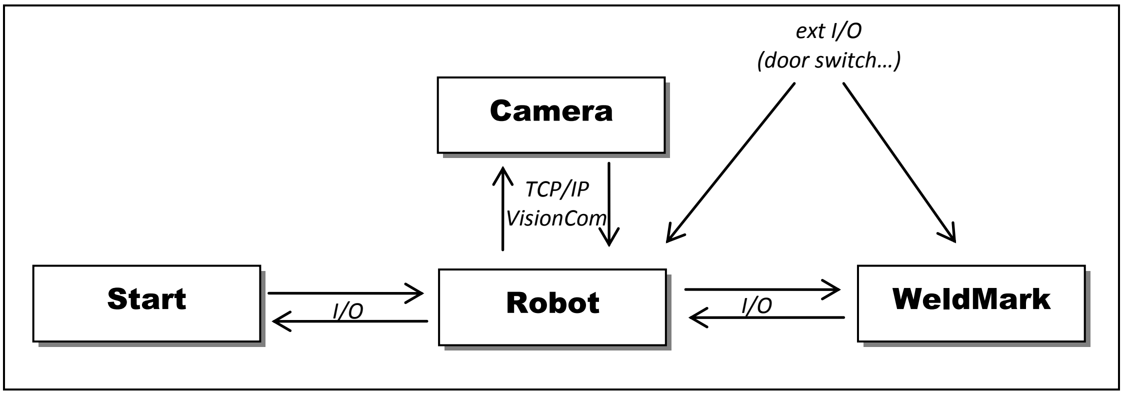


Figure 3: Concept of robot control

In the first concept, the system's logic is situated in the robot. This means, that the robot arranges the communication between each component. The dataflow is regulated in the KRL-program where I/Os can be set, pulsed and read. Those I/Os are only analogue I/Os which entails the first disadvantage: each channel is a wire running from the robot to the approximately eight meters distant laser control unit. Assuming 100 signs have to be engraved, eight wires need to run from the robot to the laser in order to encode the sign number in binary format. Two more wires are needed for the start button and the signal lamp. This leads to 80 meters of cable just for communication between the robot, the laser and the environment.

Another disadvantage of this concept is that fault cases are badly caught. If an error occurs, the KRL-program stops but the fault message can't be processed by the robot directly. Instead, the operator standing on the outside must try to correct the error, possibly leading to a complete reset of the system.

The last disadvantage is the absence of a stored program control (SPC) or the like. Without a SPC the robot can't move in automatic external mode (see 10.Automatic External mode), which entails the operator holding the KCP during the whole engraving process and pressing the clearance button.

This concept, however, also has a couple of advantages like the renunciation of a bus-system, which can be complicated to set up. The WeldMark software can work by default with six analogue I/Os on the SP-ICE-card (see 7.3.Laser and deflection unit) and react instantly to changes.

Furthermore, each interface is implemented directly in each device. In the WeldMark software, for example, a sign can be configured to be set active for engraving only if a certain bit pattern is detected on the I/Os. And I/Os can be set directly out of the KRL-program without the need to configure them first. Provided that the camera is from Cognex, the communication between the camera and the robot is likewise easy, as Robot VisionCom can be controlled with simple commands directly out of the KRL-program. Altogether this leads to a quite easy way of programming the system.

For better understanding of the concept, the following diagram shows the data flow of the system:

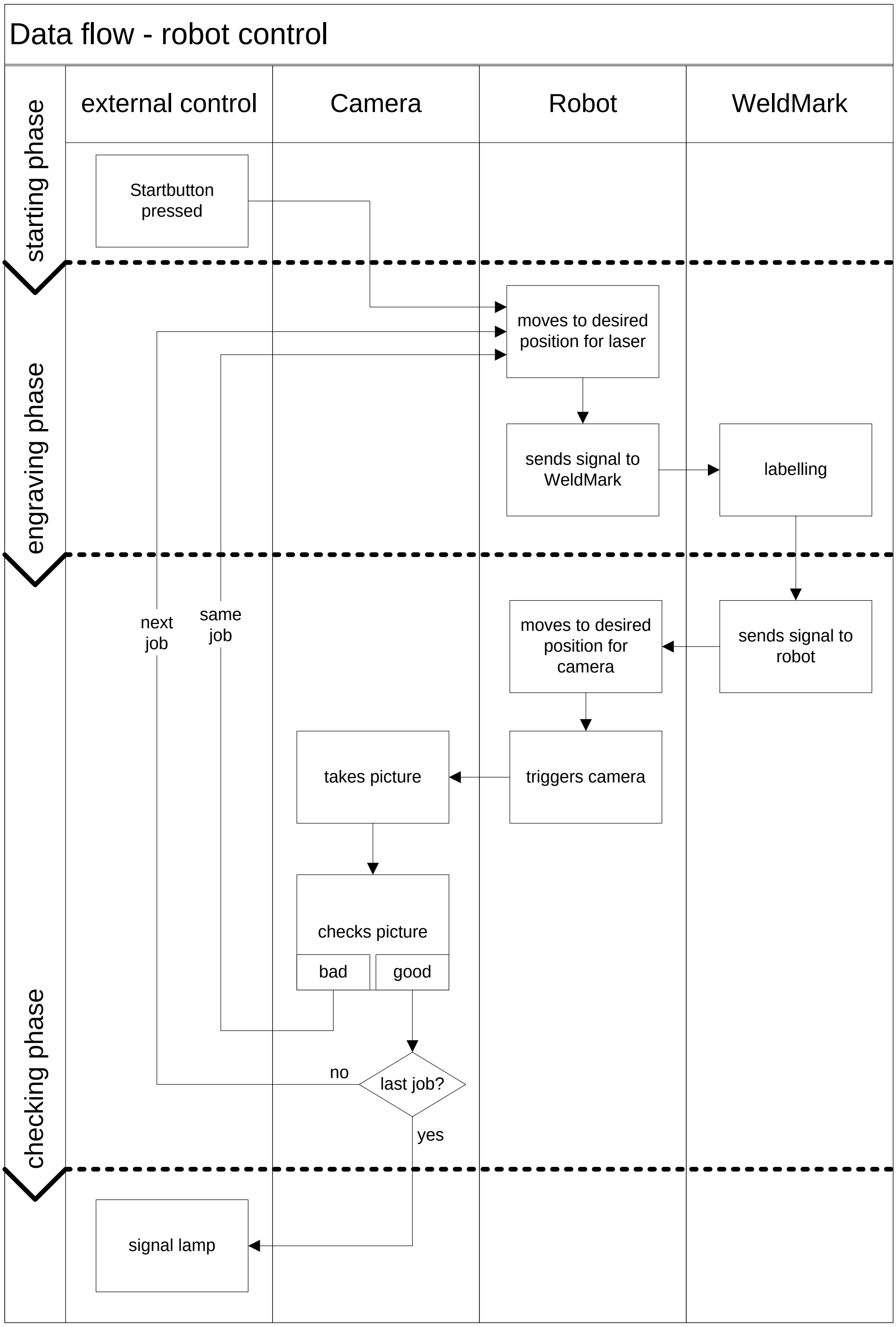


Figure 4: Data flow with robot control

6.2.WeldMark control

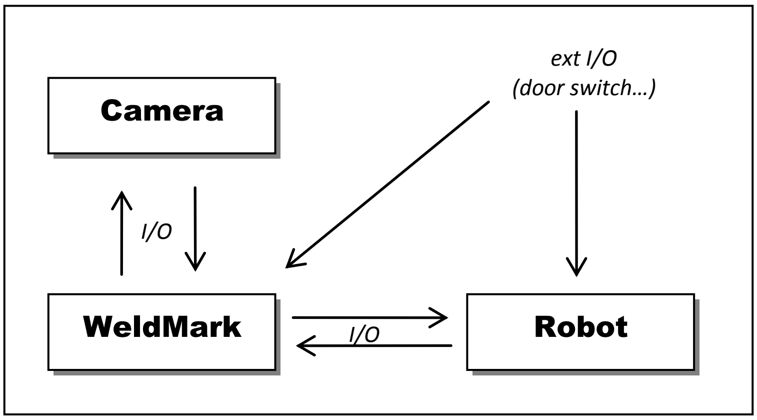


Figure 5: Concept of WeldMark control

In the second concept the main component used for controlling the system is the WeldMark software. This concept arises from the possibility of using an option in WeldMark where user defined GUIs can be created directly out of the program. The operator-view is in principle not bad, but the possibilities of configuration are highly limited and rigid. For example, you can't set several outputs at the same time, making it difficult to transmit a program number to the robot. Furthermore, different workarounds are needed, for example after the camera check has finished successfully, a signal is sent to WeldMark which should be forwarded to the robot so that it moves to the next position. This forwarding is not implementable, as WeldMark can only react with a laser-job on an input. Consequently, an empty job must be created which starts when the camera check has finished. After the job has processed an output to the robot for it to move must be set.

The long connection cables, bad error handling, and the automatic external mode already mentioned in the robot control also occur in this concept, but just as well the simplicity of implementation due to the absence of a bus system and the use of the interfaces directly out of the programs.

The camera type can be discussed as the sensor is linked to WeldMark by digital I/Os. That's the reason there's no use to procure a Cognex model, which is much more expensive than a National Instruments model. Both models support quite the same functions for generating and evaluating histograms or finding patterns. The National Instruments model can be embedded and controlled in a LabVIEW program but the Cognex model can communicate directly with the robot. Therefore, the decision in favour one model should not only depend on the engraving system but also on further projects (e.g. automatic picking of objects).

For better understanding of the concept, the following drawing shows the data flow of the system:

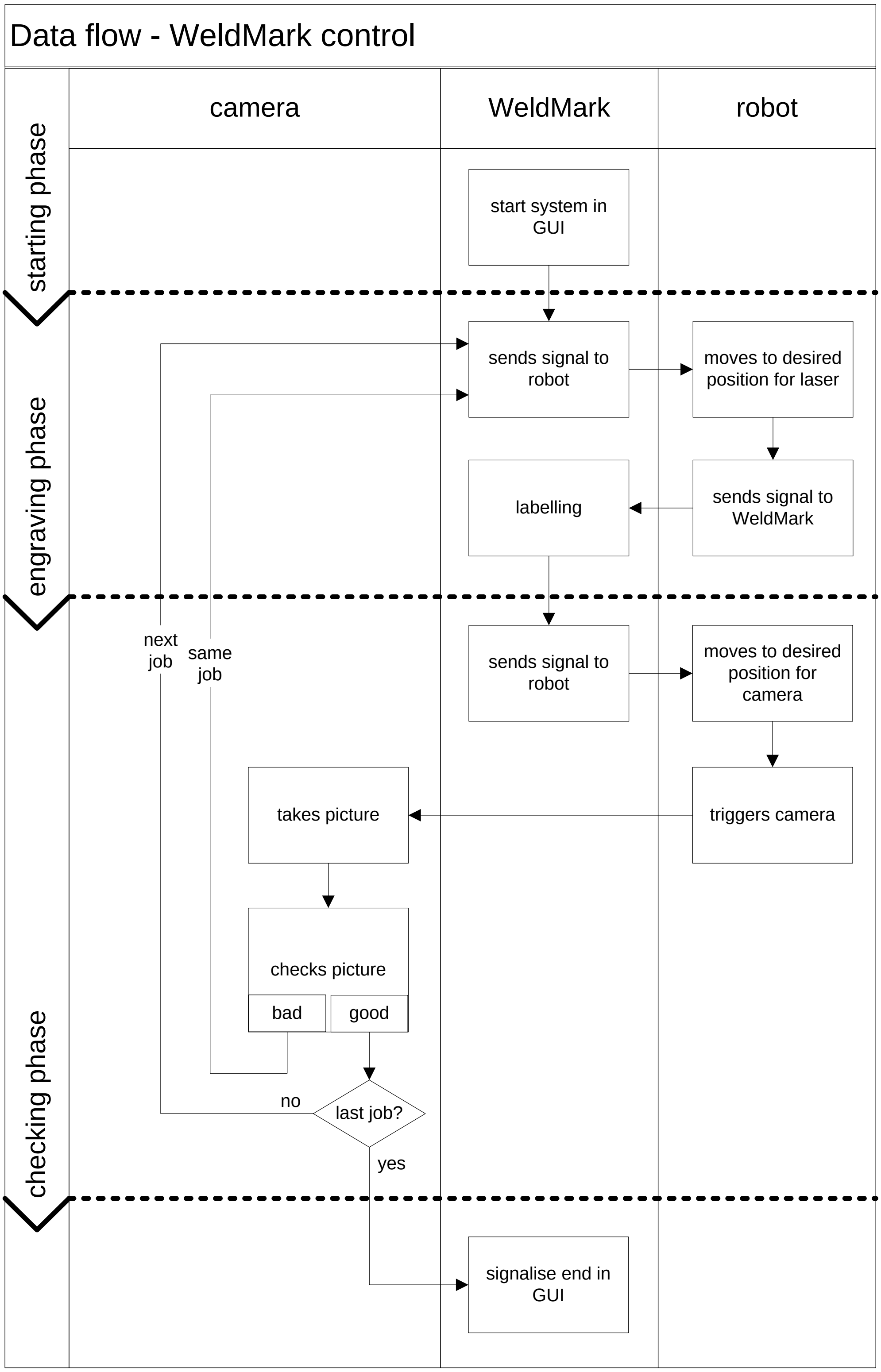


Figure 6: Data flow with WeldMark control

6.3.LabVIEW control

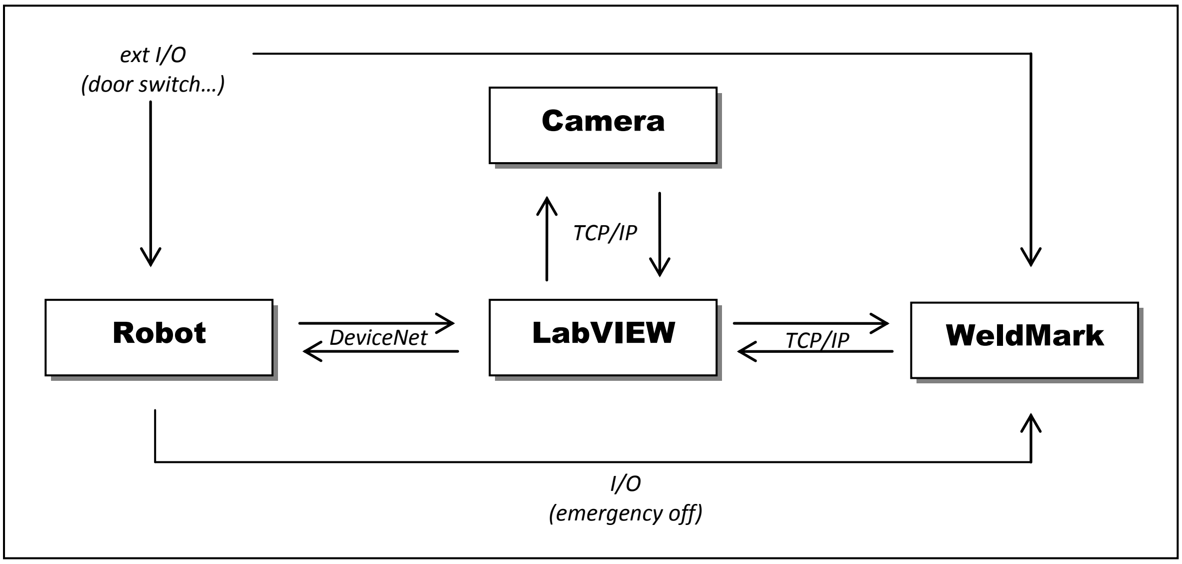


Figure 7: Concept of LabVIEW control

This concept is the first using LabVIEW as GUI and logical component. The software is standard at MBDA for industrial process measurement and control, so it seems natural to implement the GUI in this language to allow better debugging, easier retracement, and easier enhancement.

As LabVIEW is a visual programming language, it's very flexible and has a wide range of possibilities to perform tasks. For example, the communication with the components can run over every imaginable interface such as I/Os, TCP/IP or even bus-systems like Profibus or DeviceNet. Therefore, it is logical that TCP/IP is mainly used for communication between LabVIEW and the camera and between LabVIEW and the laser software. LabVIEW could also control the robot over TCP/IP ("KUKA RSI XML") but this method would intervene in a robot's layer under the security layer, which would bring out that security functions as software end switch would not work anymore and the robot could spoil itself. Another way to establish a communication between LabVIEW and the robot using the robot's safety layer is connecting both of the components by a bus-system. In this case, DeviceNet is used because, at the time of implementation, a DeviceNet card was already available.

With the communication between LabVIEW and the robot, good error handling as well as a system to simulate a SPC can be implemented. The latter allows the robot to be able to move in automatic external mode. Furthermore, the use of a bus system and network-based connection saves a lot of meters of cables which would have been necessary in a concept using I/Os. In addition, the dismounting and reassembling is much easier this way.

On the other hand, the set up and communication over DeviceNet and TCP/IP is more complicated than switching I/Os because each communication form first needs to be configured manually in each device (see 8.2.DeviceNet).

Additionally, WeldMark has the deficit not to be able to send a signal when a laser job is finished. As seen in the data flow below, LabVIEW must use a busy waiting technique to obtain certification that the engraving process is finished. The busy waiting technique means, in this case, that LabVIEW sends a request to WeldMark in regular intervals of 100ms in order to obtain the laser state. During the engraving process the laser is switched on and consequently the responded laser state is *busy* but once the process is finished, LabVIEW gets a *ready* answer and goes ahead in the program.

In terms of the camera, both models can be considered as the same discussion can be lead as in 6.2.

The last but greatest disadvantage of this concept is the poor work flow between the components due to the star-like arrangement. Each message has to run over LabVIEW, even LabVIEW doesn't have to evaluate the information. For example, after the camera has checked the engraving successfully, it must first send a message over TCP/IP to LabVIEW to continue on to the next sign. This information is then forwarded over DeviceNet to the robot. The same process occurs after WeldMark has finished the engraving process and triggers the robot to move in the checking position. A direct communication between the robot and the camera is therefore desirable and shown in 6.4.

For better understanding of the concept, the following draw shows the data flow of the system:

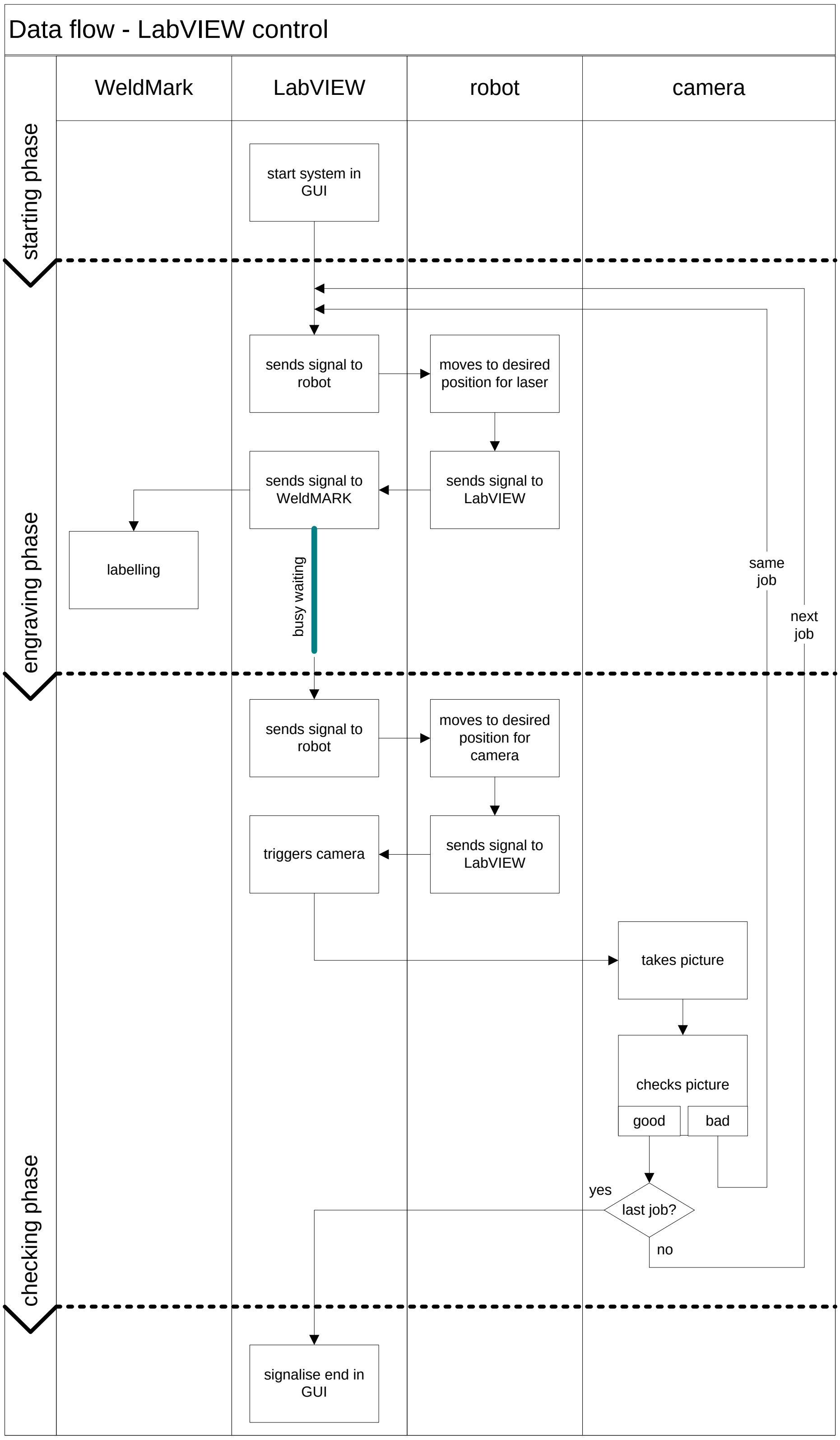


Figure 8: Data flow with LabVIEW control

6.4.Control split in LabVIEW and robot

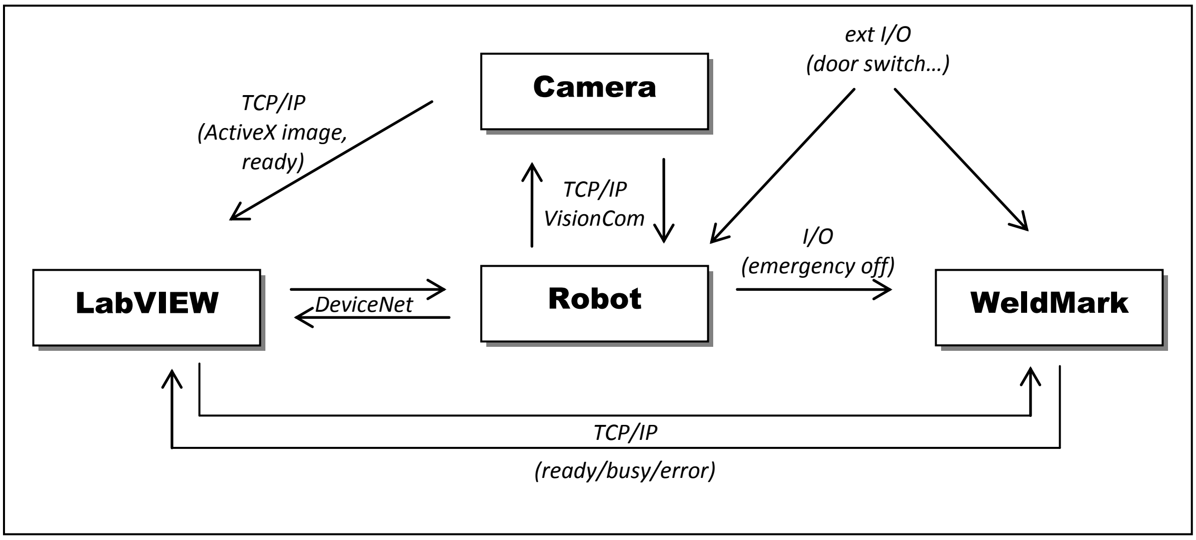


Figure 9: Concept of split control

As mentioned in 6.3., a direct communication between the camera and the robot is desirable. Thus a concept for the combination of the LabVIEW control with the robot control carries the advantages of both concepts.

The GUI and part of the logic is implemented in LabVIEW, which complies with the company's policy. At the same time, the data flow has been improved by creating a direct communication between the Cognex camera and the robot (see data flow below). Unfortunately, the robot can't establish a connection to WeldMark over TCP/IP as KUKA has not yet developed such an interface.

Concerning the hardware safety, a SPC is not necessary because the robot already has safe communication ports exactly for this purpose. Therefore, the robot is able to switch off the laser in case of failure.

A small disadvantage is that the busy waiting problem shows up in this concept. WeldMark is still controlled over TCP/IP as in 6.3.

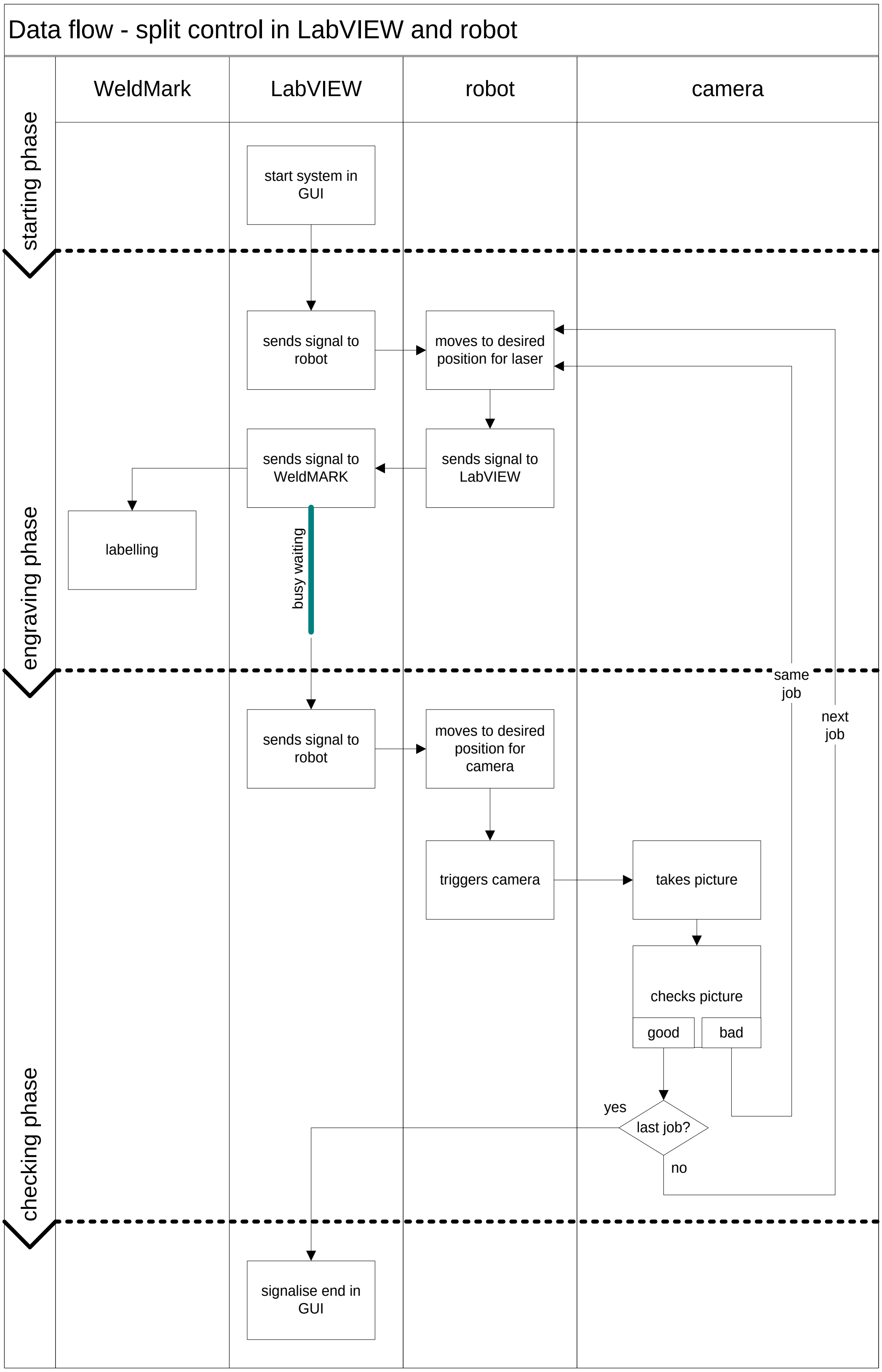


Figure 10: Data flow with split control in LabVIEW and robot

6.5.Conclusion of concepts

Summing up, the system has to comply with a list of requirements such as good data flow, easy dismounting and reassembling of the system, the use of LabVIEW as GUI, error handling, automatic external mode in order to allow a fully automated system, and hardware safety if possible without an additional SPC. All these requirements are met in the concept where the logic is split in LabVIEW and the robot. Therefore, this thesis is going to work out the details of the fourth concept.

7. Components

The engraving system is composed of several components such as the laser with its control unit, the camera for checking, the GUI implemented in LabVIEW and the robot. On the following pages the reader can have a closer look at each component starting with the robot.

7.1. Robot

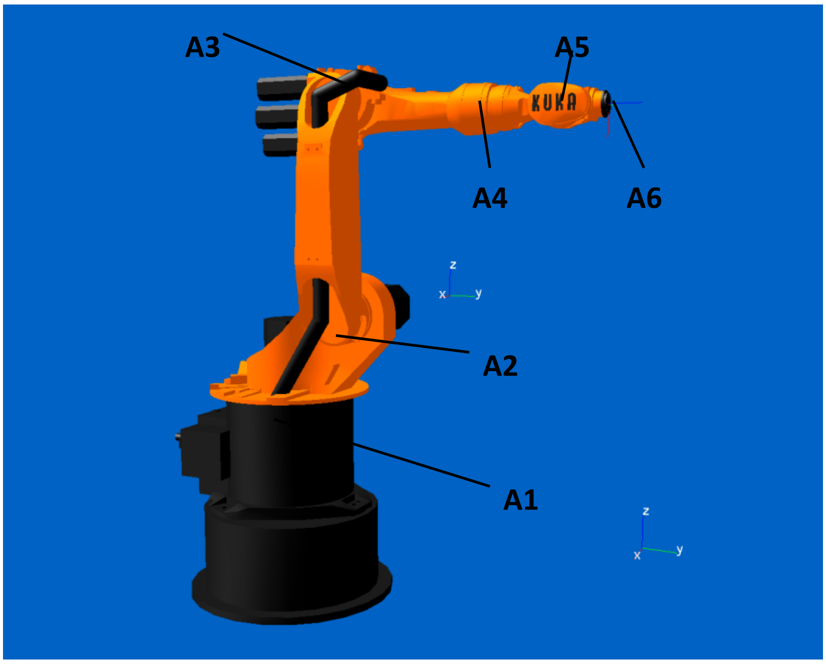


Figure 11: KR-16 with 6 axes

The robot used is a KR-16 from the German company KUKA. Besides the robot itself, a control unit KR C2 and a turnover positioner are part of the robotic components.

As you can see in Figure 11, the KR-16 has six rotatory axes, whereas axis 1 to 3 are so called main axes and axis 4 to 6 are so called wrist axes. The range of motion of each axis is shown in Table 1 below. With a volume of working envelope of 14.5 m^3, each position for laser engraving can easily be reached. The laser attachment, holding the deflection unit and the laser collimator at the flange, weights approximately 8 kg. This weight is well below the rated payload of 16 kg. The laser itself is fixed on the arm's back above A3 as supplementary load and is connected to the collimating lens by a fibre optic cable[3]. In order to obtain optimal drivability, the torques of inertia must be computed out of CATIA and entered in the robot's configuration.

An additional axis is needed for the engraving system because the launch tube must be turned so that each area can be reached by the laser. Therefore, a KPF1-H turnover positioner from KUKA is positioned just in front of the KR-16 (see Figure 2).[4]

The control unit KR C2 (V 5.5.5) is responsible for actuating both the robot and the turnover positioner. The KR C2 is a P-IV with 1024 MB RAM running Windows XP Embedded and a human-machine-interface (HMI) which is shown on the control panel that the operator holds in his hands. In the control unit, additional PCI-cards can be integrated, such as a DeviceNet-card required in our system for communication with LabVIEW in order to control the robot's automatic external mode.

Axis	Range of motion software-limited	Speed
1	±185°	156°/s
2	+35° to -155°	156°/s
3	+154° to -130°	156°/s
4	±350°	330°/s
5	±130°	330°/s
6	±350°	615°/s

Table 1: Range of motion of KR-16[3]

KUKA allows the robot to move in different coordinate systems such as the world system, the tool system, the base system and the external base system. The latter is important for the engraving system because a newly-defined base placed directly on the launch tube would result in easier point teaching. Assuming the robot's arm has to move to a point above the launch tube which is, due to the software-limitation, unreachable, in consequence of moving A7, respectively the turnover positioner, the KR-16 will keep the relative position to the launch tube and rotate around its centre-line.

[3] KUKA – KR-16 specification
[4] KUKA – KPF-1 specification

7.1.1. Singularities

There are two categories that singularities can be classified as: Workspace interior singularities and workspace boundary singularities. Workspace interior singularities are characterized and recognizable by the collinearity of two or more axes. In this case, there are infinite configurations of the axes for one and the same tool position and orientation, and infinite lines of motion where several axes have to turn against each other with unlimited velocity respectively. Workspace boundary singularities occur when the robot's flange is situated near or at the inner or outer boundary of the workspace, which happens when the manipulator is folded back on itself or fully stretched out. A consequence of a singularity is a loss of one or more degrees of freedom which can be noticed by the deficit of moving the robot's hand along one direction in Cartesian space. [5]

Due to the construction of the KR-16, there are three types of singularities which can emerge and which will be explained in the next sections.[6]

[5] Craig
[6] KUKA – course of studies

7.1.1.1. α_1-singularity

The first workspace interior singularity possible with the KR-16 is the so called α_1-singularity. In this configuration, axis 1 is aligned with axis 6 between the main and overhead area. The robot control can't clearly allocate a rotation around the plumb line.

This singularity is for the present irrelevant for the engraving system as the robot won't get in such a configuration.

Figure 12: Robot in α_1-singularity

7.1.1.2. α_2-singularity

The α_2-singularity is a typical workspace boundary singularity as the arm is completely stretched out. In this configuration, the manipulator's hand can't move centrically away and therefore looses one degree of freedom.

This singularity is also not relevant for the engraving system as the KR-16 doesn't need to reach such a point.

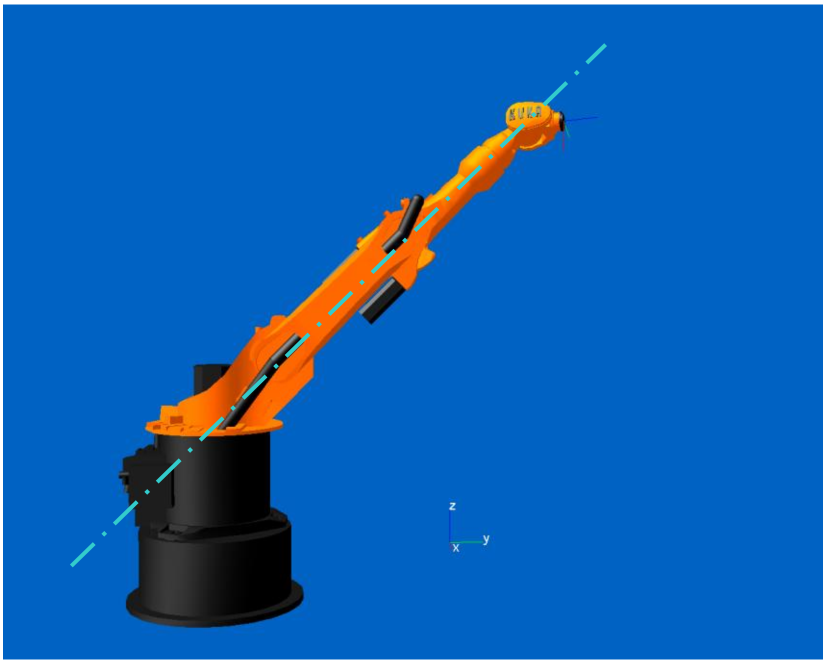


Figure 13: Robot in α_2-singularity

7.1.1.3. α_5-singularity

The last constellation for a workspace interior singularity is the zero crossing of axis 5. In this case axis 4 and 6 are collinear. As this collinearity occurs often in the engraving system, the robot is arranged slightly inclined to the turnover positioner so that the wrist is slightly inclined as well. This arrangement obviates the α_5-singularity.

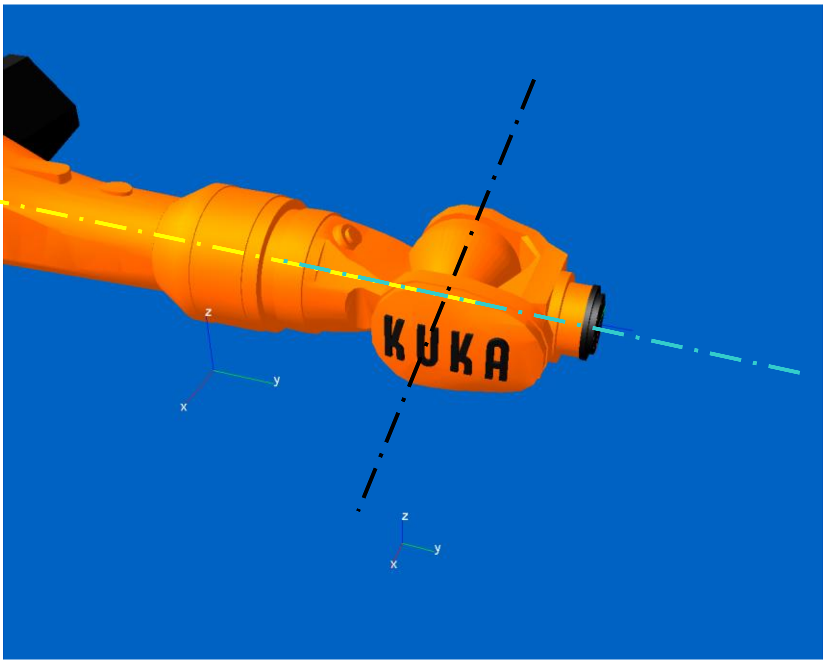


Figure 14: Robot in α_5-singularity

7.1.2. Clearness of a taught point[7]

The robot needs to be taught different positions over the launch tube to engrave the symbols. These positions are points in Cartesian space which have six degrees of freedom: three degrees for the three dimensions and further three degrees due to the three possibilities of rotation (roll in X-direction, pitch in Y-direction, yaw in Z-direction). A set with this information can explicitly determine a point in Cartesian space.

Another way to determine the position of the robot's hand in Cartesian space is considering the pivots (see Table 5). Computing a Cartesian coordinate out of the pivots is distinct thanks to the transformation matrices and is called Forward Transformation. The problem with saving just the values of the axes is that these configurations can only be interpreted reasonably by the same robot model. Running the program with the taught points on another KUKA model with six axes would not lead to the same result due to different arm length and offsets.

Consequently it is not the pivots' angles, but the Cartesian coordinates, which are relevant for being saved. As mentioned before, a set with three values of dimensions and three values of rotation can explicitly determine a point in Cartesian space. But computing the corresponding pivots' angles out of a given Cartesian coordinate is much more problematic as the result is not unique (see Table 4). This computation is called Inverse Transformation.

Therefore, KUKA saves additionally to each taught point two more values called status and turn. This additional information is saved in the extended point called *Xname_of_point* which is listed in the corresponding .dat-file of the program (see Figure 15). With the values of status and turn, a distinct configuration of the robot is possible again.

[7] KUKA – course booklet for advanced training

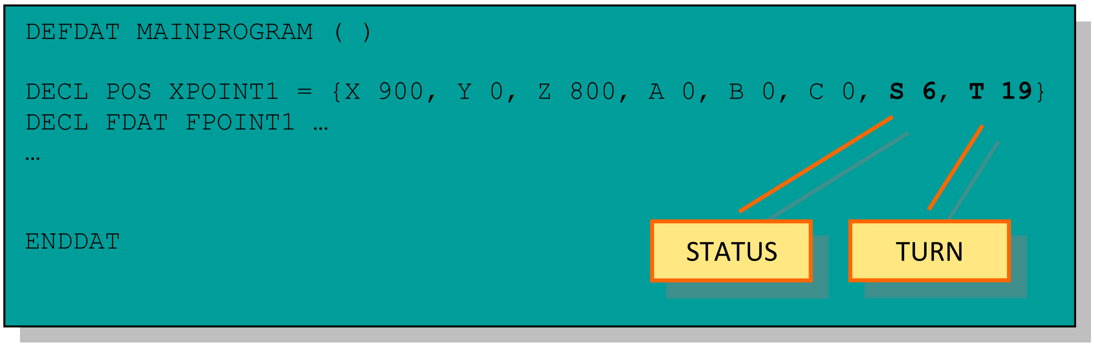


Figure 15: Extended information of a taught point in KRL

The value of **turn** is a binary coded value between 0 and 63 by reason of the six axes. Each single bit defines the sign of the pivots value for its rotatory axis.

Value	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
0	A6 ≥ 0°	A5 ≥ 0°	A4 ≥ 0°	A3 ≥ 0°	A2 ≥ 0°	A1 ≥ 0°
1	A6 < 0°	A5 < 0°	A4 < 0°	A3 < 0°	A2 < 0°	A1 < 0°

Table 2: Turn-bits on the basis of axes values

In Figure 15, for example, the extended point shows the turn-value 19. This value corresponds in binary code to 010011, which corresponds again to a configuration with axes A1, A2 and A5 in negative rotational position and axes A3, A4 and A6 in positive rotational position.

The value of **status** is a binary coded value as well, but this time only from 0 to 7 because just three binary information are need to be represented. The first information, bit 0, defines the position of the hands centre point (= intersection of the axis' prolongations A4, A5 and A6). If it is in front of axis A1 (main area), bit 0 is 0. Otherwise, the centre point is in the overhead area and bit 0 turns to 1.

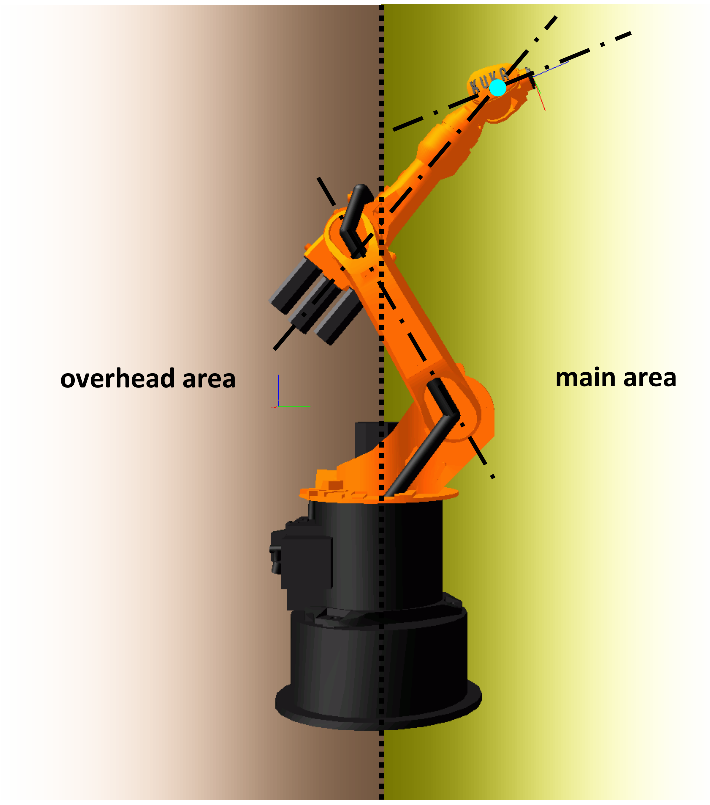


Figure 16: Main and overhead area of a robot

Bit 1 defines the arm position. In our application with a KR-16, bit 1 can be interpreted as the negation of bit 2 from the turn because the KR-16 doesn't have an offset between axis 3 and 4 (A3 < 0° → bit 1 = 0). This absence of offset means that the prolongation of those two axes have an intersection point.

If a robot has an offset between axis 3 and 4 (e.g. KR-30), the angle coat, in which the value of bit 1 changes, depends on the size of this offset.

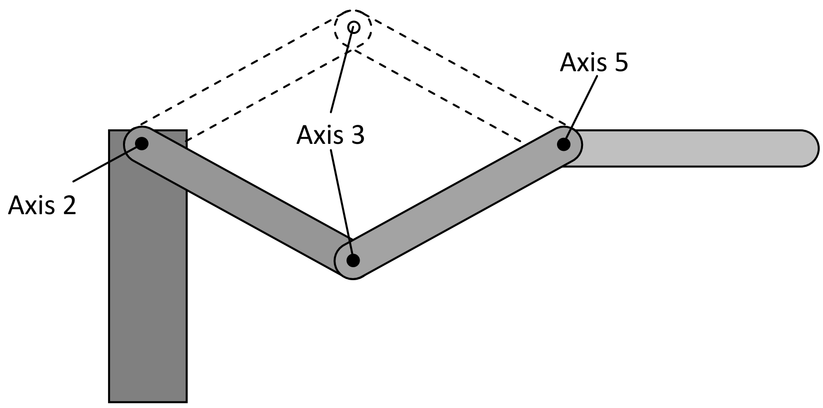


Figure 17: Schematic assembly of KR-16

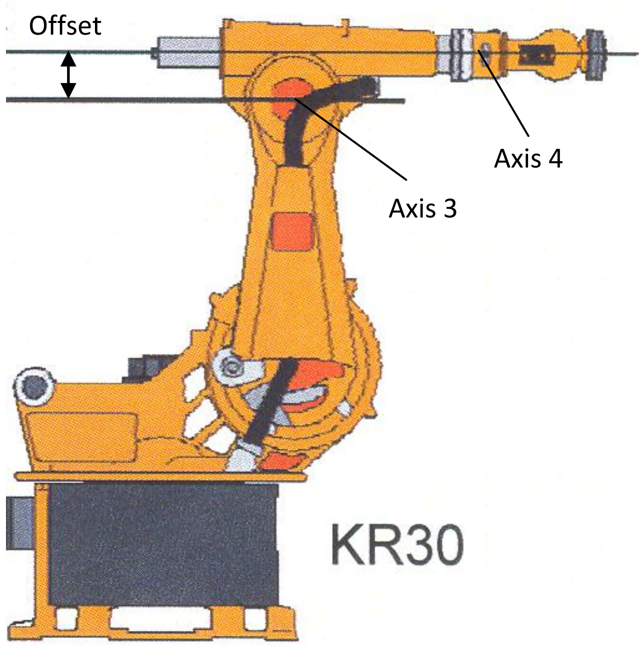


Figure 18: Offset between axis 3 and 4 shown on KR-30

The last bit (bit 2) defines the hands configuration and can simply be interpreted as the negation of bit 4 from the turn. This means that moving A5 in a positive value of degrees turns bit 2 into 1 and vice versa.

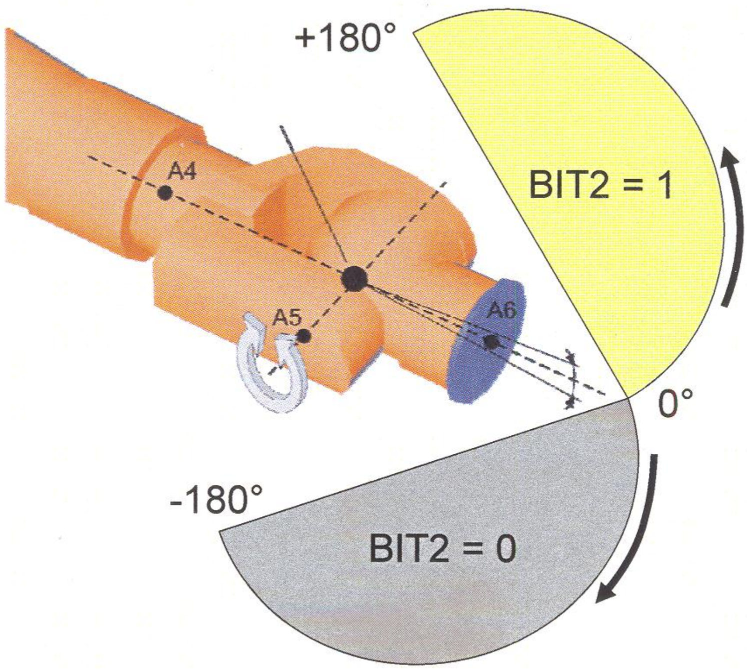


Figure 19: Definition of bit 2 relating to A5

KUKA has defined three types of movements: a linear movement (LN), a cyclic movement (CLC) and a point-to-point movement (PTP). A LN-movement is a movement along the direct connection between two Cartesian points. The positions between the start and end point are interpolated in order to get a straight connection. The CLC-movement is used to obtain a smooth, circular path by traversing a start, middle and end point. The PTP-movement compares the actual configuration of the axes and the desired configuration. Afterwards each axis moves to the desired angle by starting and ending all together whereas the slowest axis dictates the duration of the whole movement.

Only a PTP-movement evaluates the status and turn values. Therefore, the first movement in a KRL-program has to be a PTP-movement in order to obtain a definite configuration of the pivots.[8]

[8] KUKA – course of studies

The same Cartesian point with identical orientation can be reached by the KR-16 with eight different possibilities which can be differenced by the status and turn value:

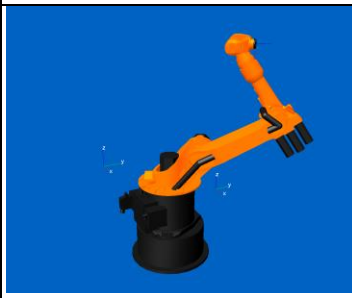
Status = B010 = D2 Turn = B000010 = D2			Status = B110 = D6 Turn = B111010 = D58
Status = B000 = D0 Turn = B100110 = D38			Status = B100 = D4 Turn = B111110 = D62
Status = B011 = D3 Turn = B000011 = D3			Status = B111 = D7 Turn = B110011 = D51
Status = B001 = D1 Turn = B101111 = D47			Status = B101 = D5 Turn = B010111 = D23

Table 3: Different configuration for the same point

The corresponding configuration of the axes:

status \ axes	A1	A2	A3	A4	A5	A6
010	30,00°	-120,00°	90,00°	30,00°	30,00°	0,00°
110	30,00°	-120,00°	90,00°	-150,00°	-30,00°	-180°
000	30,00°	-27,82°	-95,98°	16,66°	119,31°	-325,10°
100	30,00°	-27,82°	-95,98°	-163,34°	-119,31°	-145,10°
011	-150,00°	-159,55°	54,47°	195,23°	72,09°	21,78°
111	-150,00°	-159,55°	54,47°	15,23°	-72,09°	-158,22°
001	-150,00°	-102,52°	-60,45°	-132,33°	19,76°	-19,37°
101	-150,00°	-102,52°	-60,45°	47,67°	-19,76°	160,63°

Table 4: Corresponding values of angle for the same point

7.2.Camera

As the launch tube is painted by hand, different thicknesses of paint layers can occur. But the laser always engraves the signs on the first cycle with the same energy and speed, and therefore could lead to irregularities in the marking. Thus a camera system is integrated in the engraving system in order to check the readability of the signs.

The concept used requires a direct communication between the robot and the camera, which entails a sensor from the company Cognex. The sensor used in the engraving system is a monochrome In-Sight 5100 complying with the IP67-standard. According to Cognex, the In-Sight 5100c model with a colour chip does not procure more information than its monochrome pendant except for a clearer image.[9]

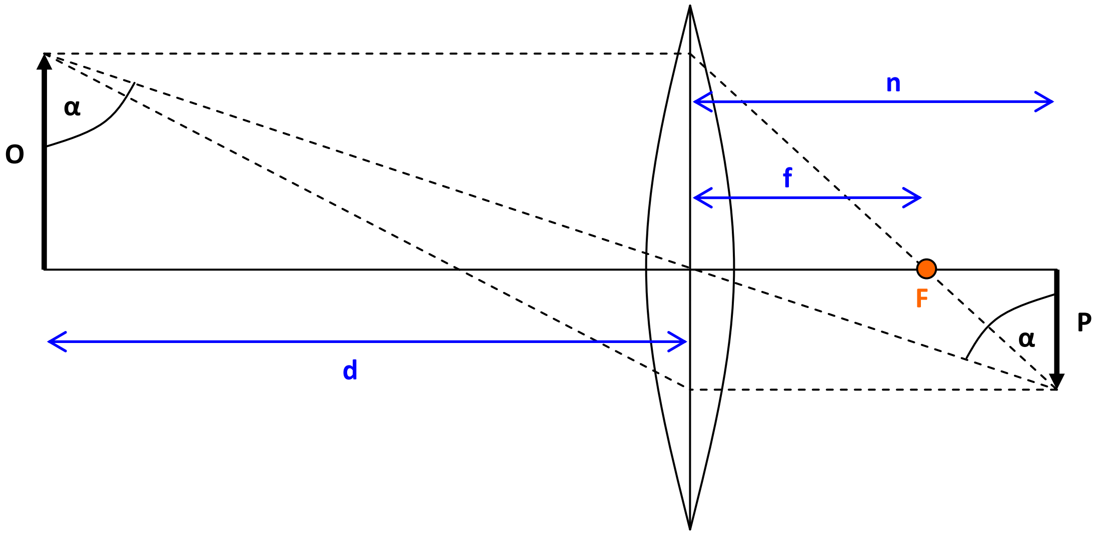
The software (In-Sight Explorer) provided with the camera allows the development of so-called jobs which can be uploaded on the camera so that the sensor can act as a stand-alone system. The direct communication between the camera and the robot over TCP/IP is provided by the software Robot VisionCOM, a beta release from KUKA also tested at BMW. Other communication forms via ModBusTCP, Profinet, KUKA Vision, DeviceNet, PROFIBUS and Telnet are possible as well but not desired in this scenario.

7.2.1. Objective[10]

The camera is equipped with a 1.25''-objective from Pentax having a focal distance of 8mm. The objective has a manual focus and aperture stop which is responsible for controlling the brightness.

For further information, Figure 20 shows the schematic refraction of a lens.

[9] Cognex – course of studies 1
[10] Cognex – course of studies 1



O:	dimension of object	P:	dimension of picture
d:	operating distance	n:	image distance
F:	focal point	f:	focal distance
α:	angle		

Figure 20: Schematic refraction of a lens

With the theorem of intersecting lines, the reproduction scale β can be defined as follows:

$$\beta = \frac{P}{O} = \frac{n}{d}$$

Another deduction of the theorem of intersecting lines leads to the thin lens formula:

$$\frac{P}{O} = \frac{n-f}{f}$$

$$\frac{n}{d} = \frac{n-f}{f}$$

$$\frac{1}{d} = \frac{n-f}{nf}$$

$$\frac{1}{d} = \frac{1}{f} - \frac{1}{n}$$

$$\boxed{\frac{1}{f} = \frac{1}{n} + \frac{1}{d}}$$

In order to get the best results with the camera, the signs to be checked should be projected as big as possible on the sensor chip. For this purpose the operating distance and the image distance must be adjusted. The operating distance can be changed by moving the robot's hand up and down and the image distance changed by actuating the manual focus. The problem with the manual focus is that the camera can only focus in a particular range around the 8mm of focal distance. In the engraving system the operating distance is approximately 37cm as this is the focal distance of the laser. But the engraved signs are not big enough on the camera screen wherefore some intermediate rings are employed. Those rings are placed between the camera and the objective in order to achieve a zoom effect. The total height of the rings has been determined empirical. A direct calculation of the total height with the formulas above is not possible as the objective is a combination of several different lenses which couldn't be specified.

Moving the robot to the launch tube is another possibility of displaying the engraved signs on the sensor chip as big as needed. Consequently less or no intermediate rings would be needed.

7.2.2. Illumination[11]

A point not be disregarded is the illumination of the launch tube. As already mentioned in the requirements, only well-defined light sources can be employed, otherwise no repeatable checking results can be guaranteed. Therefore, the engraving system is build up in a cell with only one light source namely the illumination near the camera. In order to find out which kind of illumination and which colour would be the best, a template with engraved signs was given to a company.

There are four kinds of lighting: Incident light, which is a direct illumination just above the object, diffuse light, which is used with most kind of metals to avoid reflection, transmitted light, which is a light source under an object for better detection of the contours, and lastly a so-called dark field which has a big aperture in order to obtain a better contrast what entails easier detection of irregularities on a surface.

In the tests, the best results appeared with incident blue bar-light in direct exposure. However the template was a painted plate and not a cylindrical body as the

[11] Cognex – course of studies 2

launch tube which generates reflection-straps. To avoid these reflections, a second bar-light is fixed next to the camera on the opposite side and annuls thereby the reflection-phenomenon.

The bar-light is actually a 25cm long frame containing three rows of blue LEDs. To obtain a longer lifetime, the bar-light is only switched on during the checking process as the burning time of a LED is crucial and not the number of on/off-events. Furthermore, the diodes have thereby not the time to heat up, which again has a negative effect on the lifetime.

The two light-bars are connected to a transformer where the luminosity can be modulated. In further tests, no significant difference could be retraced by varying the brightness for which reason the light-bars are operated with maximal power.

7.2.3. Interference filter for sensor protection

The purpose of the filter is the protection of the camera sensor. Because the laser beam can be reflected in every direction (see 7.3.8.Complete build-up of laser with deflection unit), the camera sensor needs to be protected. This can be realized by a hardware-shutter, e.g. a plate pushed over the camera objective, but it would at the same time be an additional component which has to be controlled by the system. Furthermore, the total weight of the holder would rise and consequently the inertia. A better and cheaper way to protect the camera sensor is using a band-elimination filter. This filter absorbs more than 90% of the light from 780nm. Therefore, the visible light (400nm – 750nm) needed for examination of the engraving passes, whereas the damaging laser beam of 1064nm is blocked (see Figure 21).

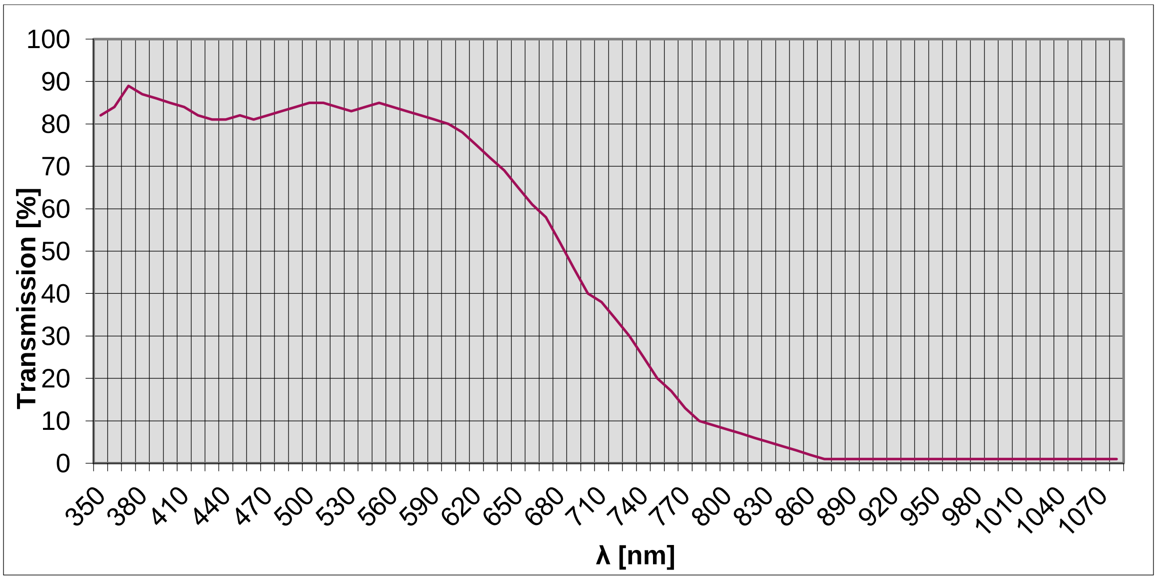


Figure 21: Transmission diagram for interference filter

7.2.4. In-Sight Software

The software for configuring the camera and creating jobs is called In-Sight Explorer. Multiple cameras can be configured and accessed at the same time by only one In-Sight Explorer. The main window contains an Excel-like sheet (see Figure 22) where the different functions needed can be inserted either by typing them in or using the drag-and-drop function. For example, in cell A0 the camera is triggered with the function *AcquireImage*. If in this image acquired a circle has to be detected, the function *FindCircle* must be inserted somewhere in the grid and related to the cell A0 as it is the cell containing the image in which the circle must be searched. In this way, all imaginable image recognition and analysis can be implemented.

When such a grid called job is finished, it can be saved either locally or directly on a sensor. The In-Sight 5100 has 32MB of Flash-space for firmware and jobs so that the camera can work completely autonomously.

As the power of the camera is coupled to the robot (see 9.Cable connection), each time the robot is shut down, the camera shuts down as well. To assure after a reboot that the camera can react properly on commands coming over TCP/IP, a standard job needs to be launched on power up which sets the sensor in online state so that it can react again on commands sent from the robot.

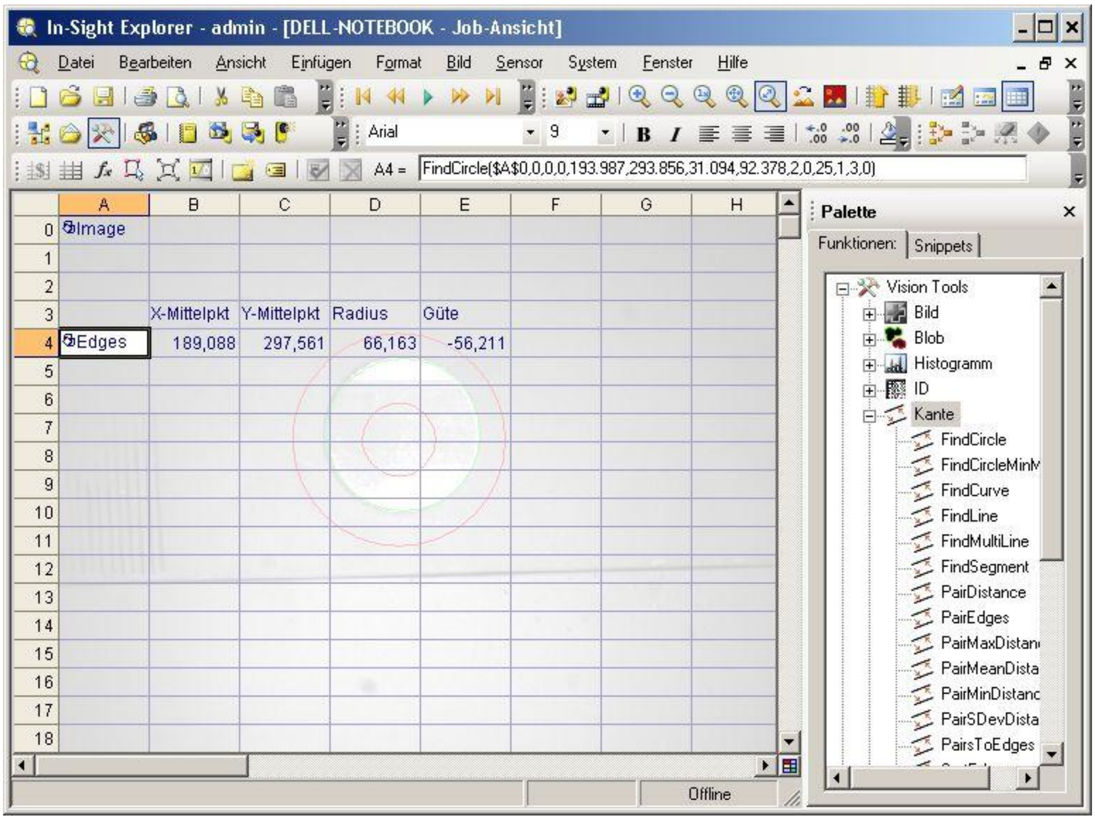


Figure 22: Screenshot of In-Sight Explorer

7.2.5. Implementation of check program

The checking jobs on the camera are necessary for assuring the quality of the engraved patterns. There are as many checking jobs as there are signs to be engraved, but each job has in common that the function *AcquireImage* is triggered over network with a Native Command sent by the robot. Each job also uses a function to find a pattern and a histogram to determine the quality and afterwards places the results in an array of string at the disposal.

The histogram just mentioned can be configured with a threshold to classify the results in good and bad samples for checking. Which threshold has to be utilized depends on the signs to be checked, but tests have shown an average value of 7. Another possibility for checking is using a template matching function. For this purpose, a picture is taken of an optimal sign and compared to the sign which has been engraved. From a certain deviation, the newly engraved sign can be classified as bad. This method has the big handicap that for each sign an optimal template has to be taken beforehand and above all those templates need all to be saved on the camera's memory, which is only 32MB and is way too small. Hence, the histogram method is used in the engraving system.

After the histogram has been created, its average value is compared to the threshold which entails a good or bad result. This result is placed in an array of strings which is located in a special cell in the grid system ready to be read out by the robot when needed. An array of strings and not only one string is implemented due to further applications in which several information need to be transmitted to the robot such as coordinates and a scaling factor.

As the whole engraving system is not time-critical, optimizing the job by adjusting the acceptance level, for example, to find a pattern is not necessary.

7.3.Laser and deflection unit

A pulsed laser (Light Amplification by Stimulated Emission of Radiation) is used for the paint ablation process. The laser on its own produces only one straight laser beam, which entails the need of a 2-axes deflection unit. Depending on the lens used, a more or less large field of marking and more or less long focal distance can be achieved. The laser is controlled by a PCI-card (so-called SP-ICE-card), which has 12 digital inputs and 3 digital outputs, and by the provided software named WeldMark.

On the laser attachment, nearby the camera, only the deflection unit and the laser's collimator are fixed. The collimator is connected by a fibre cable to the actual laser which is mounted due to its weight on the arms back above A3 and not at the flange.

7.3.1. Different laser types

There are two types of lasers: continuous lasers and pulsed lasers. A continuous laser obviously works with a continuous beam, whereas the pulsed laser works with pulsations which can be regulated in their energy and frequency. For the paint ablation a template was given to a company which ran several tests and recommended the use of a pulsed YAG-laser with 20 Watt as the material is nonorganic.[12]

For this application, the pulsed laser is better than a continuous laser because the pulsed laser can provide the energy required to heat the paint up far enough in very short time so that it evaporates. A continuous laser with the same energy, but spread over a longer time, would not attain the same result because the produced heat may have time to disperse into the bulk of the piece and therefore less material evaporates.

7.3.2. Build-up of a pulsed laser[13]

The basic elements of a laser are an external energy source, a gain medium, and a resonator. An optical resonator is a medium in which population inversion appears and is placed between two mirrors in a manner that photons cause inducted emission. Supplying external energy, also known as pumping, creates a population inversion in the gain

[12] Raylase – course of studies
[13] LASER – Funktionsweise und Anwendungen

medium. This pumping is reached in the pulsed laser used in the engraving system by a high-performance light source.

The gain medium is Yttrium-Aluminium-Granat (YAG-medium) and produces a wavelength of 1064nm. It is placed in the resonator (see Figure 23) between two curved mirrors. The photons move from one mirror two the other and back whereby the medium emits light and amplifies the beam. Thus a standing wave develops. One mirror has a coefficient of reflexion of 100%, the other one of 97% so that the standing wave can partially opt out.[14] In order to obtain a pulsed beam, an aperture is placed outside the resonator which controls the laser beam to emerge during few nanoseconds.

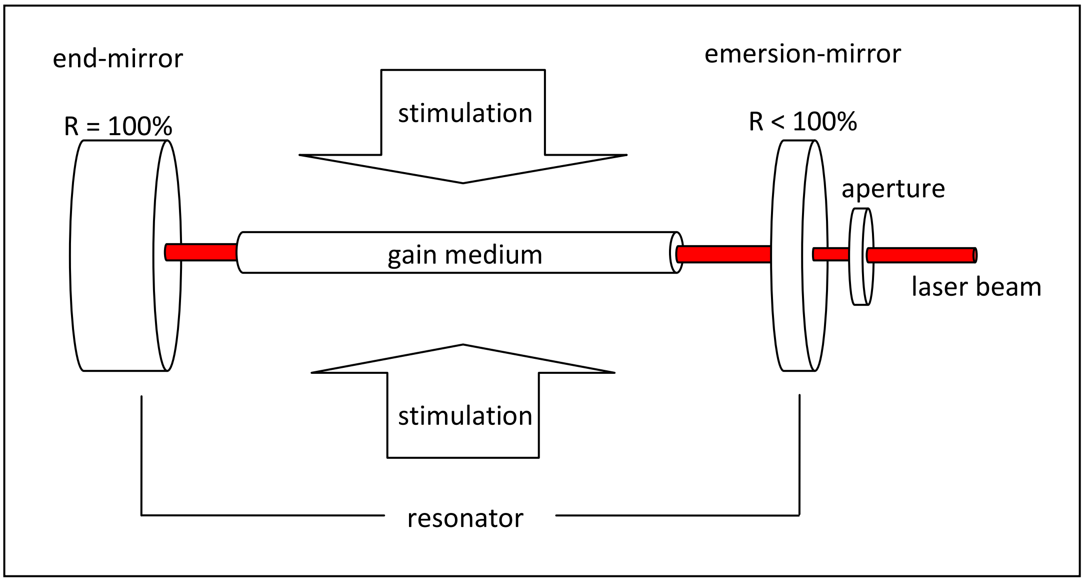


Figure 23: Build-up of a laser

7.3.3. Typical specifications of the employed laser[15]

The employed laser from IPG is a pulsed YAG-laser with a frequency domain between 20kHz and 50kHz. It can produce up to 1mJ energy per pulse and up to 200W average output power. The pulse duration can be adapted from 80ns to 500ns. The laser is structured in a compact rugged air-cooled package which is fixed on the robot's arm and a collimator, whereas each component is connected by a fibre cable. The operation is

[14] Raylase – phone call
[15] IPG – laser specification

maintenance free. However, special safety precautions must be taken because the laser is classified in Class 4 (see 11.Safety).

7.3.4. Energy loss

The laser beam runs through different media such as the fibers, the lens, and the air. Each medium has a specific transmittance which describes the amount of incident light that passes through the medium dependant on the wavelength. Beside, the transmittance, the reflection and the absorption are specific factors of the medium as well. The reflection describes the amount of incident light that is reflected and the absorption describes the amount of incident light that is absorbed by the medium. The absorption can lead to heat, light or radiation. The sum of the three factors must be, of course, 100% as no energy gets lost.

It is obvious that not the full energy exiting the resonator hits the surface to be engraved as several media have to be passed. The optical fibre cable leading the laser beam to the collimator has a transmittance of 98%, the F-Theta-lens of 93% and the air of 91%. The product of the single transmittances is ca 83%. That means that at least 17% of the beams energy disperses before the surface to be engraved is reached. In this calculation, the reflection grade of the two mirrors in the deflection unit, the collimator, the air between the resonator, and the fibre cable and the air between the collimator and the F-Theta-lens have not been considered. Leading these factors in the calculation would increase the energy dispersion.

7.3.5. Build-up of a deflection unit[16]

Out of the laser's collimator comes one straight beam. It is imperative to deflect this beam in order to create the signs which need to be engraved. Therefore, a deflection unit containing two mirrors is placed in front of the collimator (see Figure 24).

The collimated laser beam enters the deflection unit by the inlet aperture and is first deviated in Y-direction and afterwards in X-direction in each case with a mirror galvanometer. The beam exits the deflection unit through the exhaust aperture before it hits on the working surface.

[16] Raylase – 2-Achsen-Subsysteme zur Ablenkung von Laserstrahlen

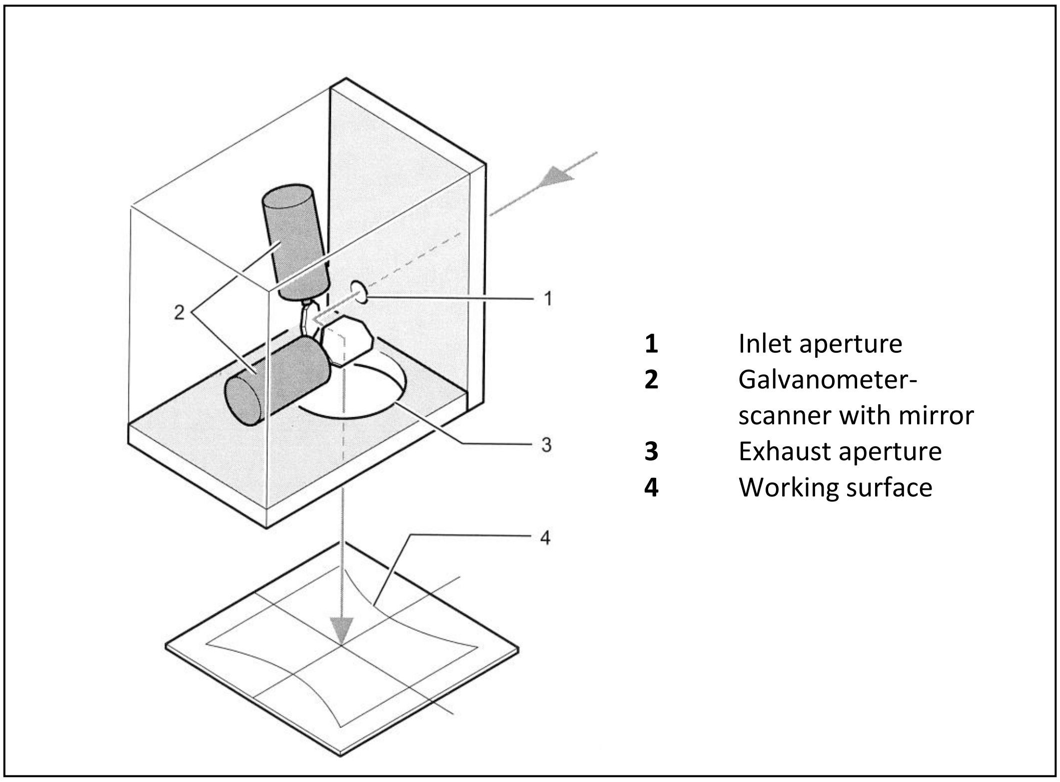


Figure 24: Schematic build-up of deflection unit

Moving the robot's hand for drawing the signs would also work but is much more complicated as each sign must be taught as an own KRL-program. Furthermore, the interplay between the robot and the laser must be highly coordinated as the robot has accelerating and braking phases in each movement which entail different beam exposure of one spot on the surface.

7.3.6. F-Theta-lens

Before the deflected beam hits the working surface it runs through a lens which is fixed under the deflection unit. This lens defines the focal distance and the size of the engraving field. Having a smaller engraving field obviously entails a higher precision and a better paint ablation effect.

The lens employed is a so-called F-Theta-lens from Raylase with a 9mm aperture, a focal distance of 254mm and a resulting engraving field of approximately 16cm x 16cm.

7.3.7. Correction of image

As the laser beam traverses several components, a couple of unintentional deflections occur which can be remarked in a deformation of the sign to be marked. Furthermore, the working surface is bent, which involves a further deformation. These deformations need to be measured and corrected.

In the following points, a square should be marked by the laser system and the figures show the belonging deformations.

7.3.7.1. Deformation due to two-mirror-deflection

The first deformation evolves from the deflection unit, more precisely from the two mirror galvanometers. The deviation in X-direction can be accomplished consistently but the deviation in Y-direction has a concave shape. This deformation can be traced back to the arrangement of the mirrors. Having the first mirror, thus the mirror responsible for the Y-deviation, in a maximum or minimum position and the second mirror, thus the mirror responsible for the X-deviation, in the zero position would entail that both mirrors abut against each other. Therefore, the first mirror is slightly moved back to the centre position in order to avoid a collision. The problem is that, while the second mirror is in the zero position, 100% positive deviation of the Y-direction is not the same as when the mirror is, for example, in 70% positive deviation. Hence this protective measure leads to the deformation shown in Figure 25.

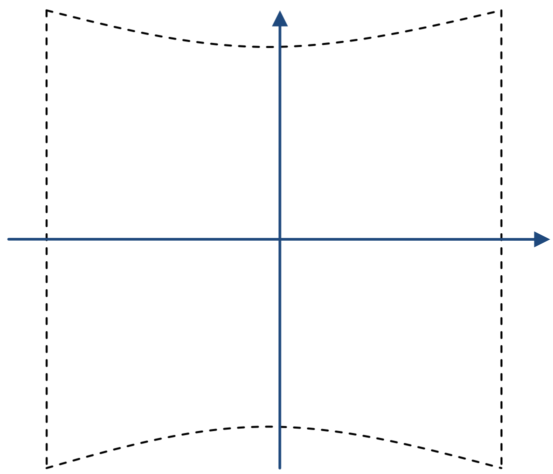


Figure 25: Deformation with two-mirror-deflection

7.3.7.2. Deformation due to F-Theta-lens

Another deformation arises from the F-Theta-lens. The laser beam is deviated unequally due to the spherical lens surface. Thereby each beam with another angle of incidence is refracted differently. The more the beam gets to the border of the lens, the less the deviation is perceivable.

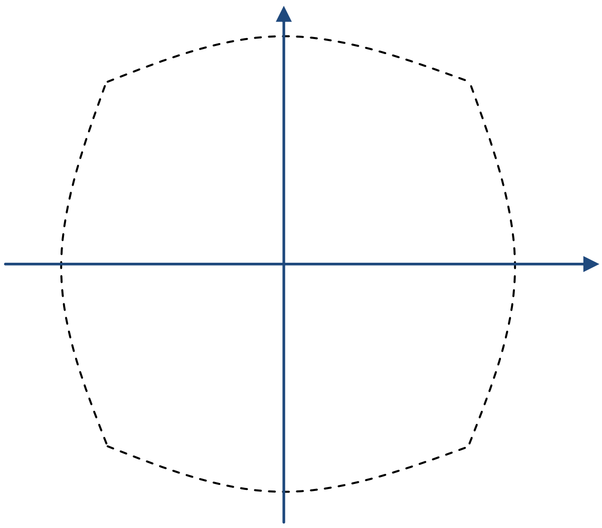


Figure 26: Deformation with F-Theta-lens

7.3.7.3. Combination of both deformations

The combination of the deformation due to the deflection unit and the deformation due to the F-Theta-lens can be seen in Figure 27. The resulting deformation is the addition of the two deformations:

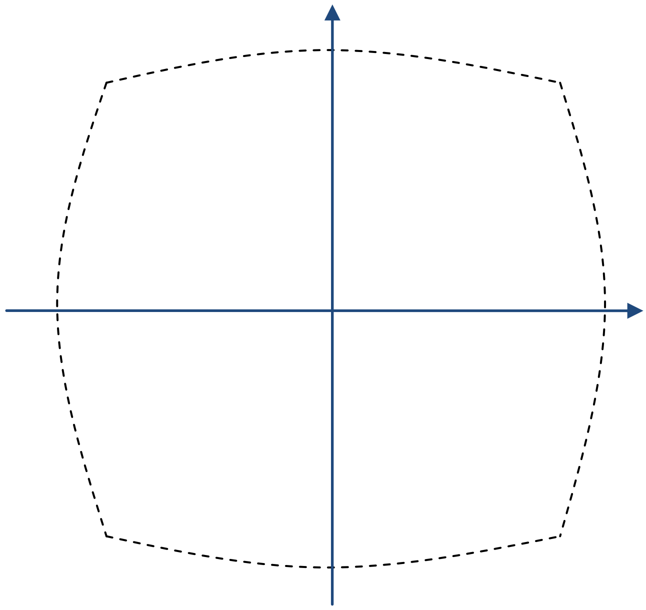


Figure 27: Addition of both deformations

7.3.7.4. Deformation on cylindrical body

The last deformation appears because the signs are engraved on a cylindrical body and not on an even body. In theory, the laser beam starts from a point between the two mirrors in the deflection unit. It covers the smallest distance by running straight down. The more the beam is deflected in the Y-direction, the longer the distance becomes due to the cylindrical shape of the launch tube. If an additional deflection in the X-direction is performed, the beam runs a few millimetres more than it would run on an even surface (see Figure 28). Mathematically spoken, a dilation has happened in this point. The cycle modification factor in this point can be computed by dividing the distance between the centre of the sign and the point marked by the distance between the centre of the sign and the point, which would have been marked on an even surface.

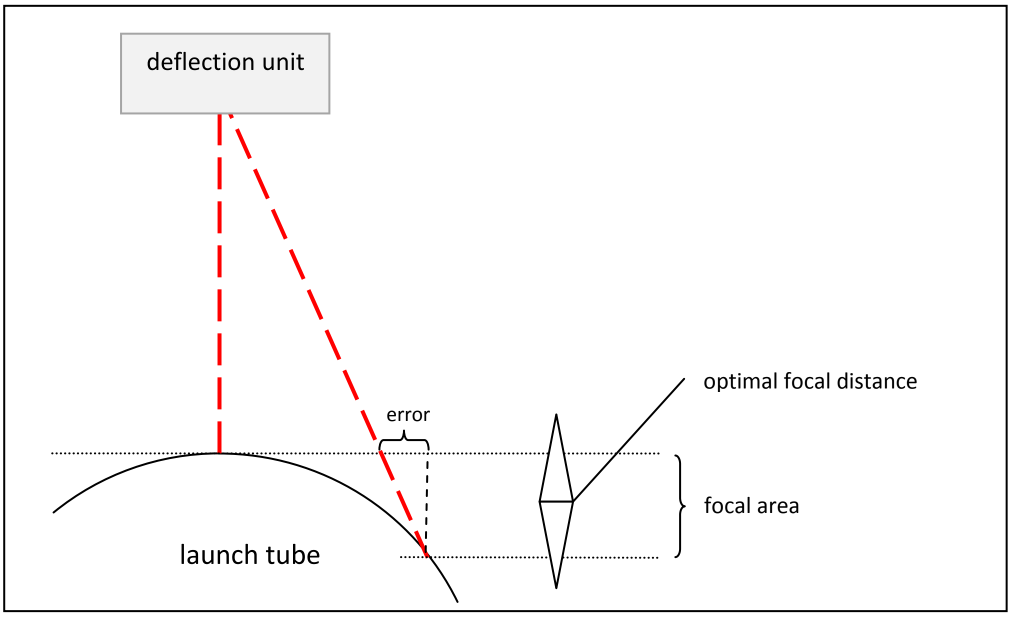


Figure 28: Lateral view of laser beam

The deformation occurring on a cylindrical body with a non calibrated lens is shown in Figure 29.

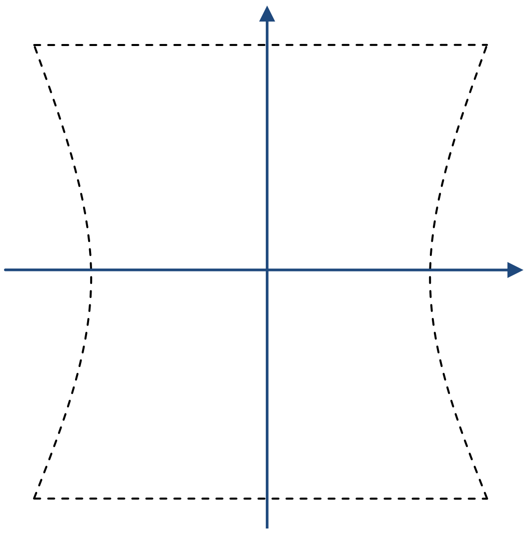


Figure 29: Deformation on cylindrical body

7.3.7.5. *Resultant correction for cylindrical body*

When combining the three deformations by summing them up, a resultant deformation appears. It is necessary to correct this resultant deformation so that the proper sign arises again. Some edges need to be pulled and some edges need to be pushed in order to obtain a uniform square again (see Figure 30). This very task can be performed with a program provided by Raylase called *correditor*. In this program, a so-called correction file can be created which can afterwards be imported in the laser control software.

The configuration of this file is straight-forward: First of all, a square with the non calibrated lens must be marked on the launch tube. Then the desired square has to be drawn on the tube. The divergence between both models at predefined points must be measured and typed in the adequate fields of the correction program. The number of the correction points (5 x 5, 9 x 9, 17 x 17, 33 x 33, 65 x 65) depends on how big the model is and how accurate the measurement can be executed.

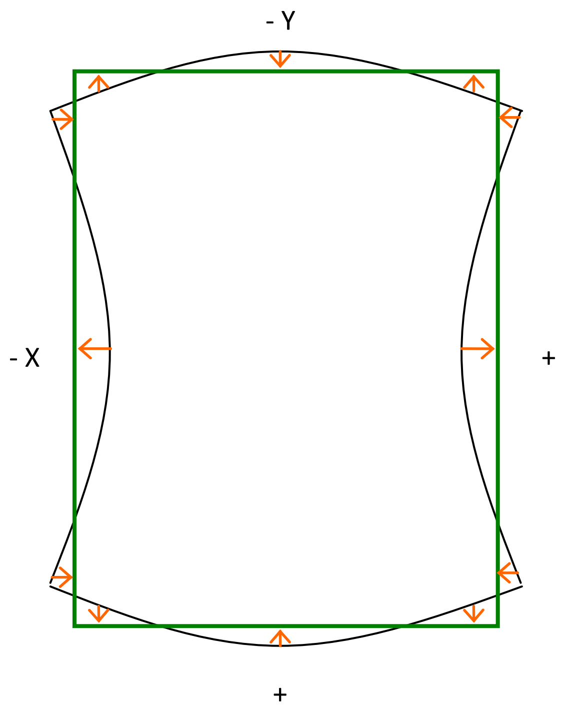


Figure 30: Correction of deformation on cylindrical body

For the laser engraving system, the configuration of the correction file is performed with 9 x 9 point with a square of the size of 200 x 120 mm and measure accuracy of 0,5mm. Using 17 or more points would not entail a significant amelioration with this measure accuracy as the deviation in the 17 points is in each case under 0,5mm (observed in test carried out). It is, however, possible to perform the fine-tuning with 17 x 17 points by visual judgement.

7.3.8. Complete build-up of laser with deflection unit

After having spoken about the laser, the deflection unit and the F-Theta-lens, the focus lays now on the complete arrangement of those components. Except for the laser itself, the collimator, the deflection unit and the lens are fixed to the laser attachment.

The collimator must be aligned in such a way, that the laser beam passes the protective casing and enters the deflection unit by the inlet aperture without hitting the enclosure. Therefore, grub screws are fixed around the collimator and permit a very fine tuning. Unfortunately, Raylase didn't develop a system for easy fixing of the protective case or the collimator at the deflection unit. The inlet aperture is a simple hole without any marks or notches.

The deflection unit is placed at the front of the laser attachment and fixed with two screws and a bail. Changing the deflection unit entails, of course, a new alignment of the collimator. The exhaust aperture of the deflection unit has a screw thread where the F-Theta-lens can be fixed.

The complete build-up is fixed at the robot's flange and it must be ensured that enough freedom of action is available and the focal distance can be kept.

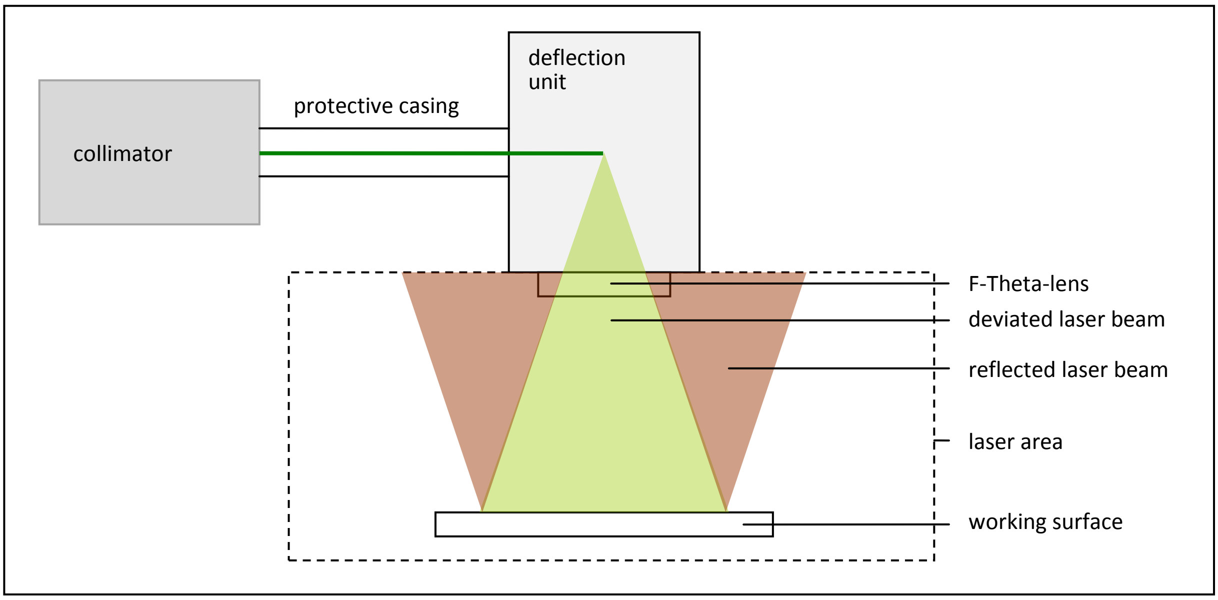


Figure 31: Interaction of laser and deflection unit

7.3.9. WeldMark Software[17]

Raylase provides with the deflection unit the corresponding software called WeldMark. The software controls the laser and the deflection unit with a PCI-card (SP-ICE-card) which is built into the control unit.

WeldMark is an intuitive, easy-to-learn program with different GUIs. The expert GUI allows for example every configuration, whereas the operator GUI can be configured very restrictively so that the user can just start and stop a predefined job. The software is not specialized on one laser type and can actually control different deflection units simultaneously. This could be advantageous in time-critical case scenarios. Besides letters with different fonts and simple geometric figures, WeldMark can also mark barcodes and matrix-codes. Furthermore, drawings and figures can be imported amongst others as bmp- or plt-files. The latter is important for the engraving system, as the signs are mostly existent in CorelDraw where they can be exported to a plt-file. It is recommended to use vector graphics, otherwise the laser works off a bmp-file by starting in one corner and moving to the bottom line by line, regardless if dots have to be marked or not. A laser-job

[17] Raylase – Homepage

with an imported plt-file is therefore faster and more precise so that, for example, drawn through lines are marked at once and not with single dots.

The software also allows a remote control with self-provided host-programs like LabVIEW. This function is possible because of the external control over RS-232, TCP/IP or Profibus.

7.3.10. Test series

In order to figure out which configuration of the laser would be the best, several tests were run with modulated parameters. Two different lenses were used and therefore two different working distances due to the specific focal distances (254mm, 100mm). Also the pulse duration, the energy per pulse as well as the marking speed have been changed, which leads to the most observable differences in the engravings.

Table 5 shows that more tests were run with the first lens, as the working space is bigger than the space produced with the second lens. The paint thickness identifies the size of the first film on the launch tube. It should be mentioned here that each additional 25µm of paint thickness means that the painter has to spray an additional coat on the launch tube, which entails higher time and material costs. The result score goes from 1 to 5, 5 being a perfect result. The marking speed indicates the laser beams velocity moving on an even surface. Furthermore, the fill spacing can be changed. This factor defines the interval between two parallel running lines. Choosing the last two factors too small leads to literally firing of the material. The last parameter in this test series is the so-called style. WeldMark allocates three different styles for engraving:

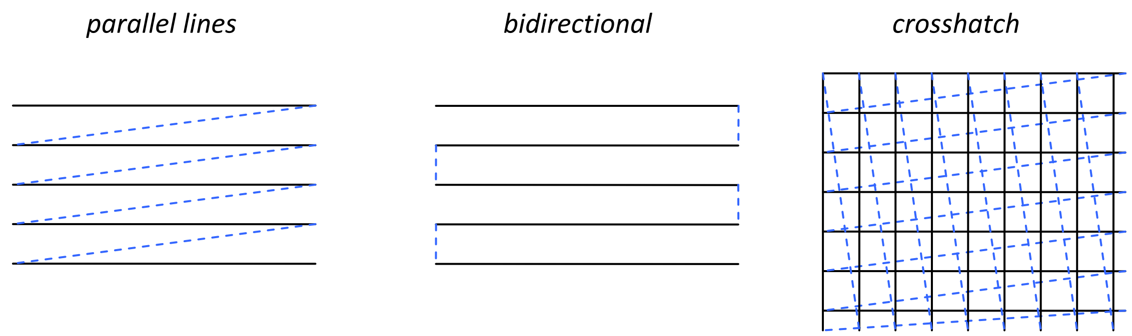


Figure 32: Different engraving styles

Configuration	working distance [mm]	Frequency [KHz]	Laser power [%]	Marking speed [mm/s]	Style	Fill spacing [mm]	paint thickness [µm]	result
a	366	20,00	80	550	parallel	0,137	25	**4**
b	366	20,00	40	200	bidirectional	0,137	25	**5**
c	366	20,00	80	550	crosshatch	0,05	25	**1**
d	366	35,00	40	550	parallel	0,10	50	**2**
e	366	35,00	80	200	crosshatch	0,05	25	**0**
f	366	35,00	80	550	bidirectional	0,05	25	**1**
g	366	50,00	20	550	parallel	0,137	50	**0**
h	366	50,00	40	550	crosshatch	0,05	50	**3**
i	366	50,00	80	400	bidirectional	0,137	25	**5**
j	155	20,00	40	550	parallel	0,137	50	**3**
k	155	20,00	80	550	crosshatch	0,137	25	**5**
l	155	35,00	40	200	bidirectional	0,05	50	**3**
m	155	50,00	80	550	bidirectional	0,137	25	**5**

Table 5: Laser tests with different parameters

The parallel style is technically seen as good as the bidirectional style, but it takes more time because the laser beam has to be lead back to the beginning of the new line. On the other hand, the engraving with the crosshatch style is sometimes too hard because each point is traversed by the laser twice, which leads to a burnt surface (test e). This style takes more time as the bidirectional style as well. Therefore, the bidirectional style is the style preferred.

Engraving with a high energy and fast marking speed (test i) seems to entail the same result as marking with less energy and slower marking speed (test b). A staff member from Raylase advised using the second configuration results in more accurate engraving.

The tests j to m have been ran for the sake of completeness as a second lens was available, but this lens was never seriously considered to be employed.

The test helped determine that configuration b is the best for the purpose of this project because the bidirectional style is employed, the first paint coat is 25µm and the combination of applying less power with a lower velocity is used.

7.4.LabVIEW

Beside the robot, the main logic of the engraving system is situated in a program implemented in LabVIEW 7.1 (see 6.4.Control split in LabVIEW and robot). LabVIEW is a graphical programming language from National Instruments. It is mainly used in measurement and automation technology. The software consists of a front panel which forms the user interface and a block diagram where the visual program code can be inserted. The programs, also called Virtual Instruments, can be compiled for Windows-, Linux- or LabVIEW real-time operating systems, for FPGAs and for microcontroller depending on the LabVIEW-module employed.[18] For the purpose of this bachelor's thesis, only the LabVIEW-module for Windows-compilation was used.

LabVIEW is utilised for providing the human-machine interface (HMI) and for acting as a SPC, otherwise the robot could not move in automatic external mode (see 10.Automatic External mode). In the following both tasks are described more precisely.

7.4.1. Graphic User Interface

The operator standing on the outside of the cell sees only the GUI. Therefore, all the information required should be represented in a clearly arranged manner. On the top, the camera screen with the particular checking information can be seen. On the bottom, the number of the actual program running and an initialising button are arranged. The initialising button is required to start the program so that it can communicate with the robot over DeviceNet. The state display shows the actual state of the system. The values available are *ready*, *error* and *finished*. Lastly the GUI can be closed by pressing the stop-button.

[18] LabVIEW homepage

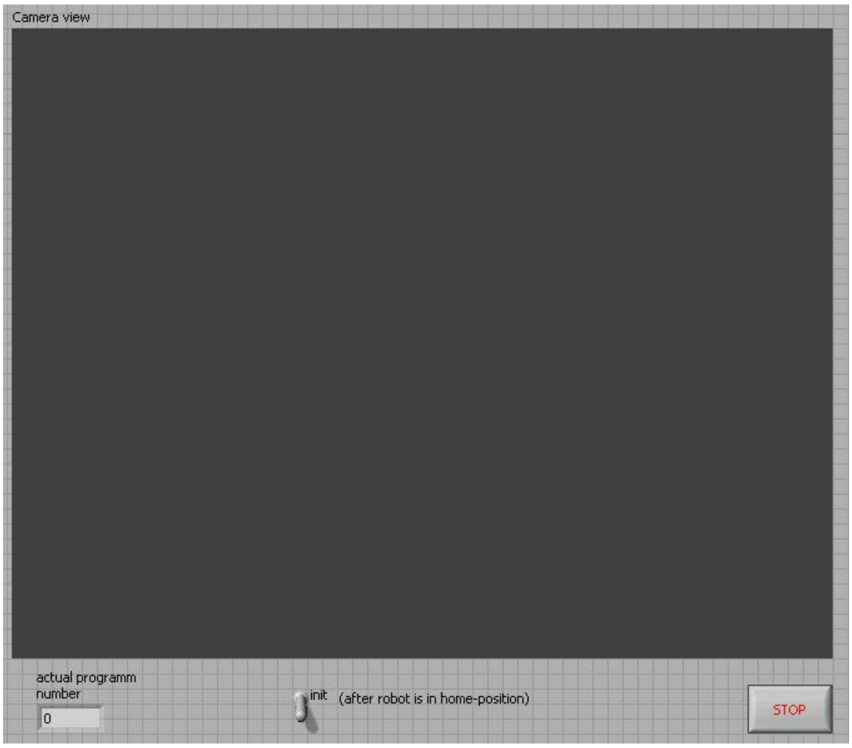


Figure 33: GUI with camera screen

The associated block diagram (Figure 34) shows on the lower left side how the state machine is initialised, how the global variable PGNO standing for the program number is set to 0, how the camera screen is embedded with an ActiveX component provided by Cognex in the front panel, and how WeldMark is started with a script. In the figure above, the connection over DeviceNet is established with the robot. The input and output data is updated regularly in the loop where the state-machine is located as well. This state-machine switches the outputs and reacts on the inputs (see Figure 35 and Figure 37).

An occurring error is passed outside the loop and handled at the end, as well as the laser software shut down, when exiting the GUI.

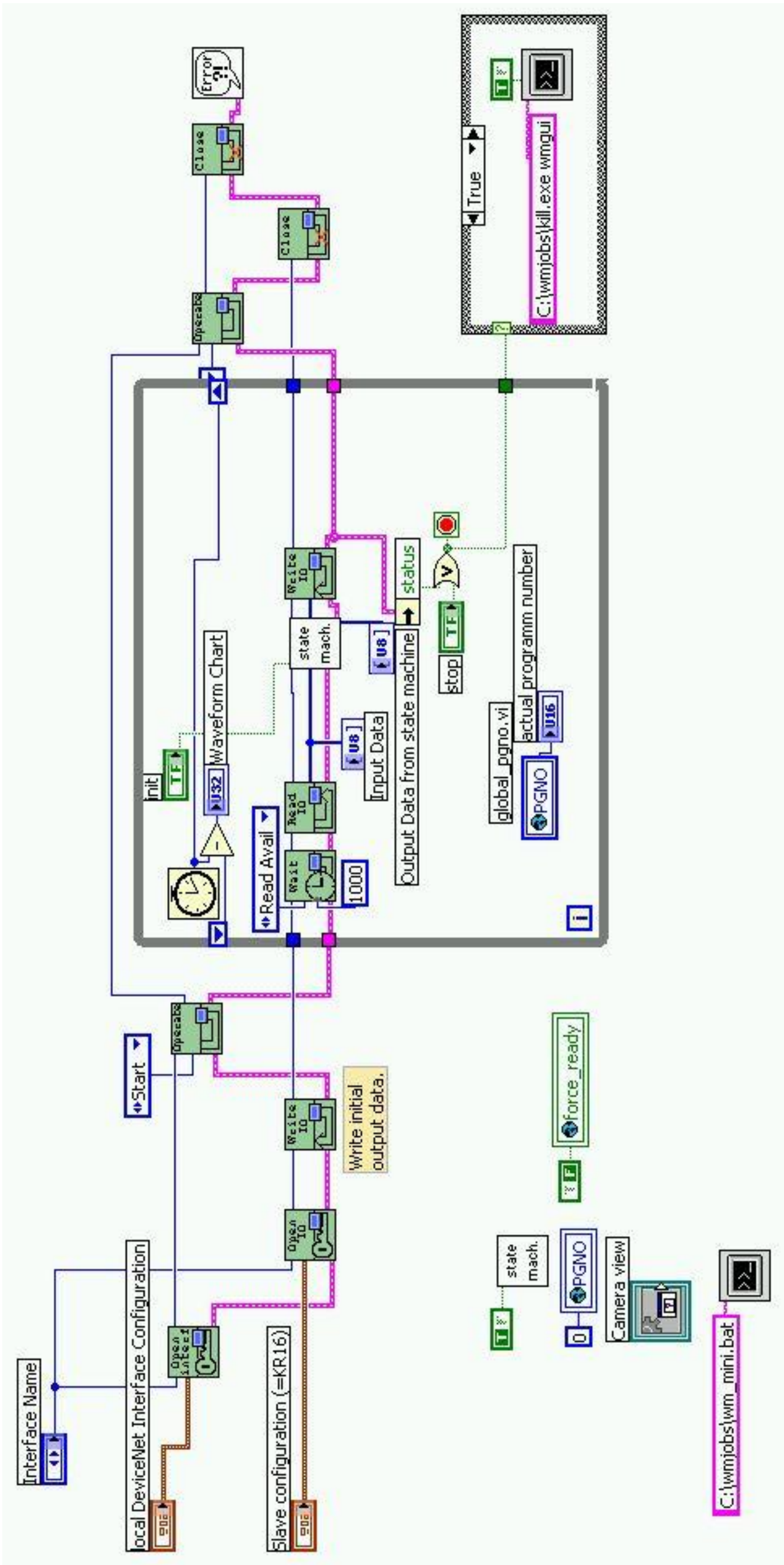


Figure 34: Blockdiagram of GUI

7.4.2. Interaction with robot

As already mentioned, LabVIEW needs to communicate with the robot over DeviceNet. In order to send information to the robot, the output data is manipulated by setting single bits (see Figure 35) to true or false. This manipulated bit-pattern is sent immediately over DeviceNet in the superior VI (see Figure 34).

After in Figure 35 the bits *$MOVE_ENABLE* and *DRIVES_OFF* have been set successfully, the state-machine jumps from the actual state *set_move_enable_drives_off_T* into the next state which is here *wait_user_saf_T*.

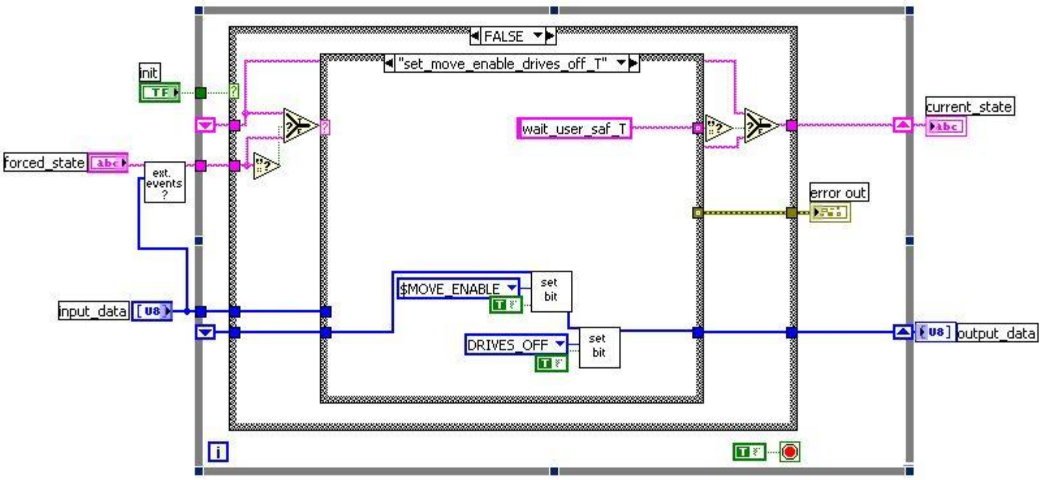


Figure 35: Setting signals to the robot

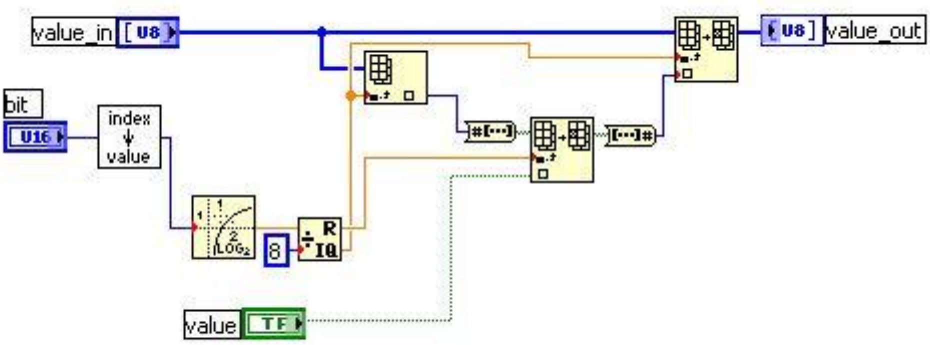


Figure 36: Setting a bit in the output data

In order to get information from the robot, the input data is read by the subVI GetBit.vi (see Figure 38). If, for example, in Figure 37 the bit defined as *STOPMESS* is not set, the state-machine stays in the actual state *wait_stopmess* until the bit is set. In this case, the state-machine jumps into the state *set_conf_mess_F_ext_start_T*.

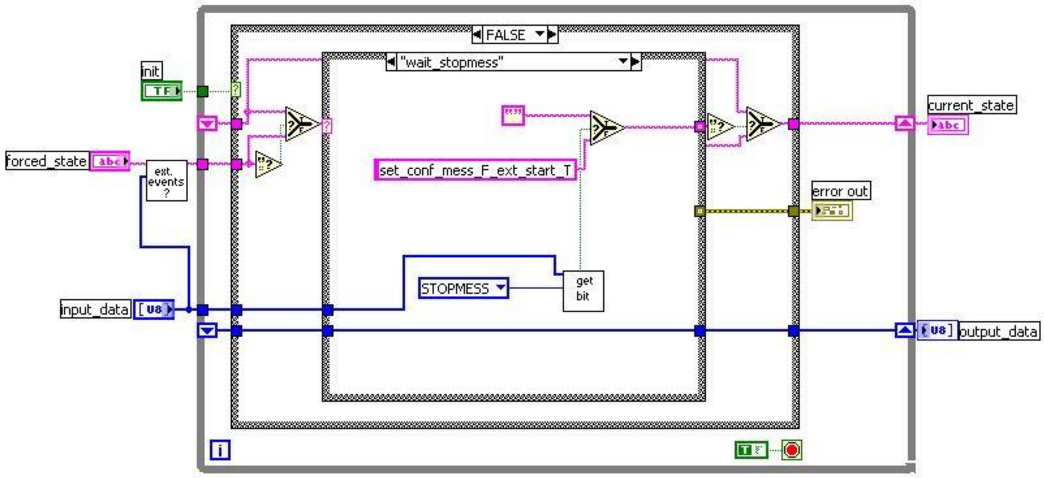


Figure 37: Getting signals from the robot

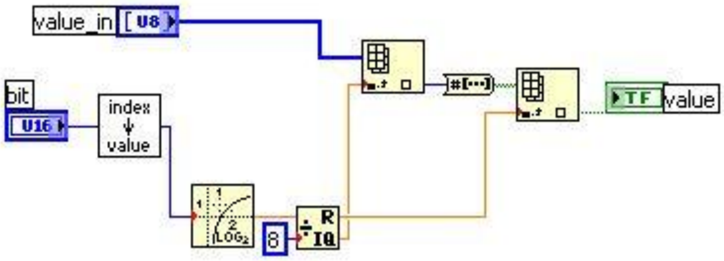


Figure 38: Getting a bit from the input data

Figure 39 shows all the states which have been created. It is not obligatory to jump from one state only to the next state. Cross-jumps and jumps to earlier states are possible as well, which enables a reusability of some states.

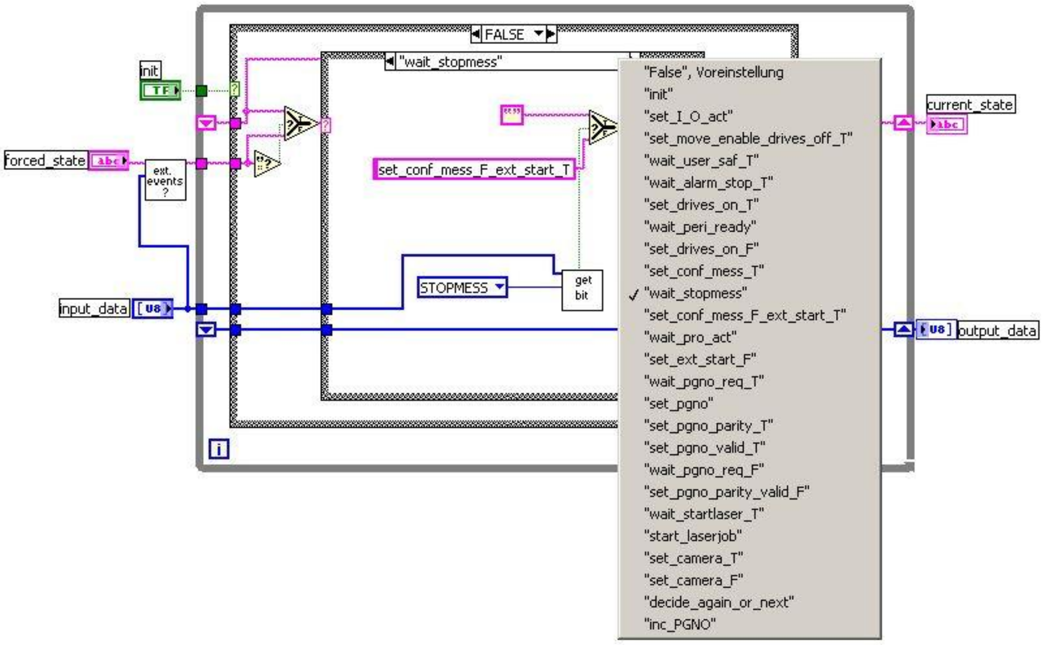


Figure 39: Sequence of states

7.4.3. Interaction with WeldMark

LabVIEW must also interact with the laser software over TCP/IP. Therefore, a subVI has been created (see Figure 41). This subVI is started in a special state named *start_laserjob* in the state-machine. It returns only a Boolean value which is false while the engraving is running and true when the engraving has finished.

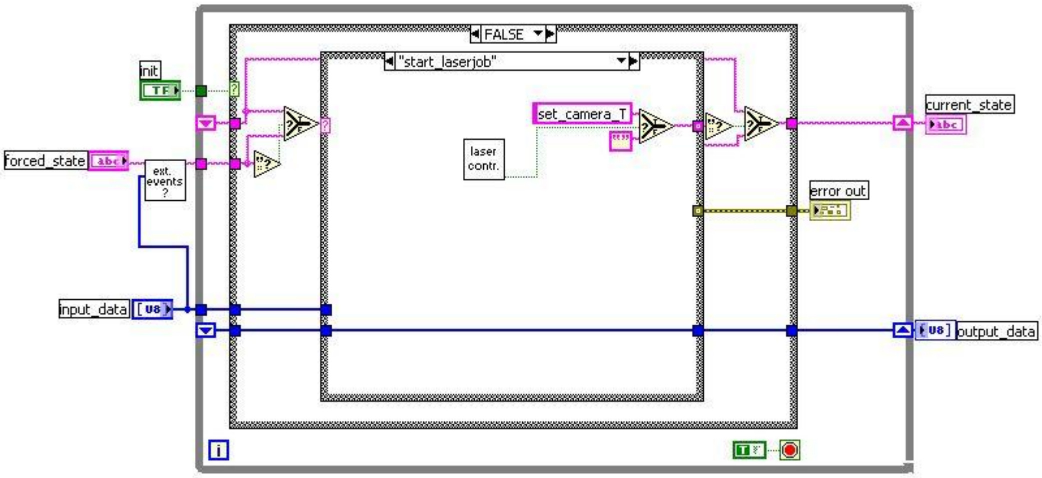


Figure 40: Integration of the laser-subVI in the state-machine

The laser subVI is built similar to the GUI: First, a TCP/IP connection is created, then data is sent to the laser software. After reading out the data the connection is closed and the error cases are caught.

When starting this subVI, first the variable *finished* is set to false. This is the Boolean value the state-machine is reading out. Then a couple of commands are sent to WeldMark like setting the software in a host-controlled state, loading the correct file (dependant on global variable *PGNO*), and starting the engraving process. After waiting 500ms, an answer should come back from WeldMark acknowledging the commands. At this moment the engraving has started. For this reason in cycles of 500ms, the state of the laser is requested. Just after the status-answer turns from *2301* to *2300* which corresponds to a completed laser-job, the TCP/IP connection is closed and the variable *finished* is set to true so that the state-machine jumps into the next state.

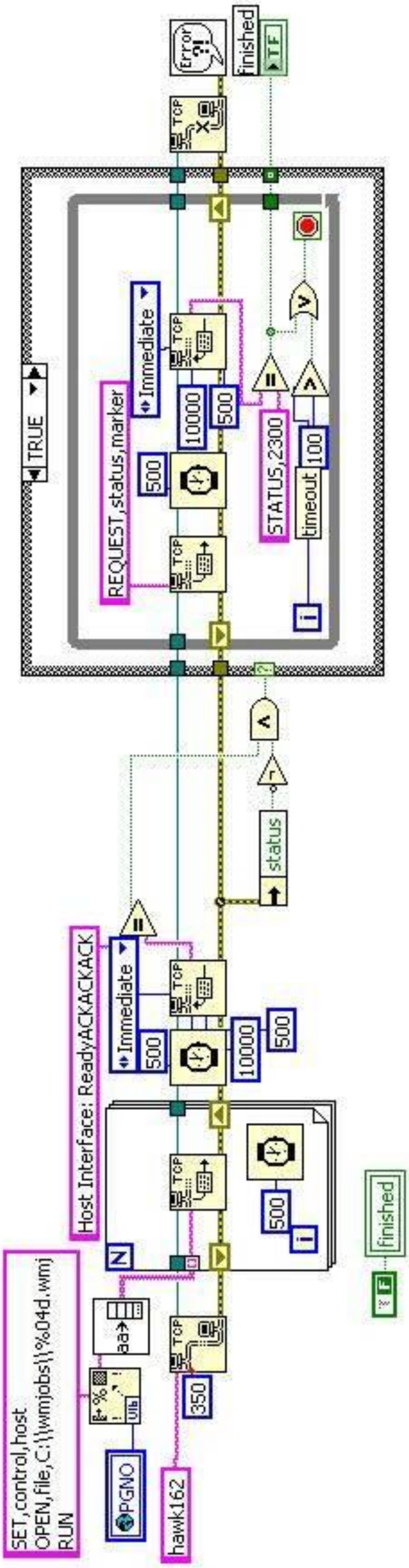


Figure 41: Blockdiagram of laser control

8. Interfaces

For communications between the components different interfaces can be employed. There are, for example, simple digital I/Os in which only one signal per line can be transmitted. Besides TCP/IP connections over Ethernet, bus-systems can be used as well, such as DeviceNet or Profibus. For system-intern interaction of components the use of dlls is also possible. This kind of communication would be possible between LabVIEW and WeldMark if both softwares were running on the same machine. The interaction of the camera with the robot is performed with a beta version of Robot VisionCom from KUKA, which again uses basically again the TCP/IP protocol and therefore has already been listed.

8.1.VisionCom

VisionCom is a software in development which is tested at the moment by BMW. After talking to some staff from KUKA, it was possible to obtain this software as well.

In the actual version only one Cognex-camera can be used by the robot which is sufficient for the engraving system. The connection parameters have to be configured in the robot's registry (the robot runs a version of Windows XP Embedded). In the path HKEY_LOCAL_MACHINE/SOFTWARE/KUKA Roboter GmbH/Options/KRVisionCOM the keys "ipAdress", "portID" and "Password" are changeable. After closing the registry the changes take immediate effect.

Now the access on the camera out of a KRL-program must be implemented. This can be done by using the function *visionCOM* with the native commands of the camera as parameters. The result set is split afterwards in the strings needed and the information processed in the next program lines (see Figure 42).

```
DEF example( )
INI

PTP HOME

tpReturn=visionCOM("SO0")           ; set camera offline
tpReturn=visionCOM("LF0000.job")    ; load file 0000.job

tpReturn=visionCOM("SO1 SW8 GVE000")
; set camera online, take a picture, give value of cell E000

...

SREAD(CAMValueReturn4[],STATE,OFFSET,"%d %f
%d",dummy1,dummy2,cam_result)

...

IF cam_result==1 THEN
      ; next job
ELSE
      ; redo job
ENDIF

...

ENDDAT
```

Figure 42: KRL source code with access to camera

The INI-line in this KRL-program contains not only the regular initialisation information but further information for VisionCom.

8.2.DeviceNet

DeviceNet is a communication protocol/field bus based on CAN (Controller Area Network) which is often used in automation industry to interconnect control devices. In the engraving system, the computer running LabVIEW and acting as master is connected to the robot acting as slave. Up to 63 slave devices can be connected to a CAN with one obligatory device configured as master although each device gets a unique ID, a so-called MacID.

8.2.1. Definition of digital I/Os

The robot needs to know which inputs or outputs are connected to which device. Therefore, the I/Os must be configured in the file iosys.ini on the robot. As the engraving system is a system that is set up from the very beginning, the I/Os can be defined at will:

Type	reserved	device	I/Os in use
input	1 – 32	LabVIEW	1 – 17
output	1 – 32	LabVIEW	1 – 30
input	65 - 72	Beckhoff-module	65 – 72
output	65 – 72	Beckhoff-module	65 – 72
input	73 – 90	gripper	73 – 90
output	73 – 90	gripper	73 - 90

Table 6: Definition of digital I/Os in the robot

The Beckhoff-module is a device for additional remote digital I/Os. They could be useful for later applications. And the gripper is a 8kg unit which can be fixed at the robot's flange instead of the engraving attachment. The gripper could also be useful for later applications.

8.2.2. LPDN-Scanner card

The LPDN-Scanner card is installed in the robot and necessary for the communication over DeviceNet with LabVIEW. The multifunctional card which is built in by default has indeed a DeviceNet port but this port can only be used as master. In the engraving system, the robot has to be configured as a slave, which entails the use of the additional LPDN-Scanner card. But the multifunctional card can still be used for controlling the Beckhoff-module or the gripper.

In LabVIEW, the connection over DeviceNet must be configured with the right parameters of the robot. As LabVIEW is the master in this CAN, it receives the MacID 0 and the robot receives the MacID 1 being the first slave device. The output length defined in number of output bytes is naturally the input length of the robot (see first row in Table 6) and consequently has the value 4. The same applies for the input length. The DeviceMacId corresponds to the slave device where the connection should be established, so in this case the robot with the MacID 1. And finally, the expected packet rate can be adjusted. In the engraving system, this value has been left untouched at 200 as the robot uses this rate by default.

8.3. TCP/IP

TCP/IP is a common network protocol. It is used in the engraving system for communication between LabVIEW and WeldMark, between the robot and the camera and between the camera and LabVIEW. The communication between LabVIEW and WeldMark is the only one where the programmer can interfere as this communication is completely set up in LabVIEW. The robot controls the camera with the software Robot VisionCom, which uses as basic protocol TCP/IP as well. But the software engineer can not intervene in the packets sent. The same applies with the communication between the camera and LabVIEW as LabVIEW uses an ActiveX-component to display the camera screen.

9. Cable connections

The single components such as the robot, the camera, the laser and so on must be able to communicate with each other. Furthermore, the supply of energy must be established. How the cable connections are realized and what kind of communication runs over the connections is shown in Figure 42 below.

The DeviceNet connection between the robot and LabVIEW, as well as the TCP/IP connection to the robot, the camera, and WeldMark, comply to the split control discussed at the beginning of this thesis (see 6.4.Control split in LabVIEW and robot).

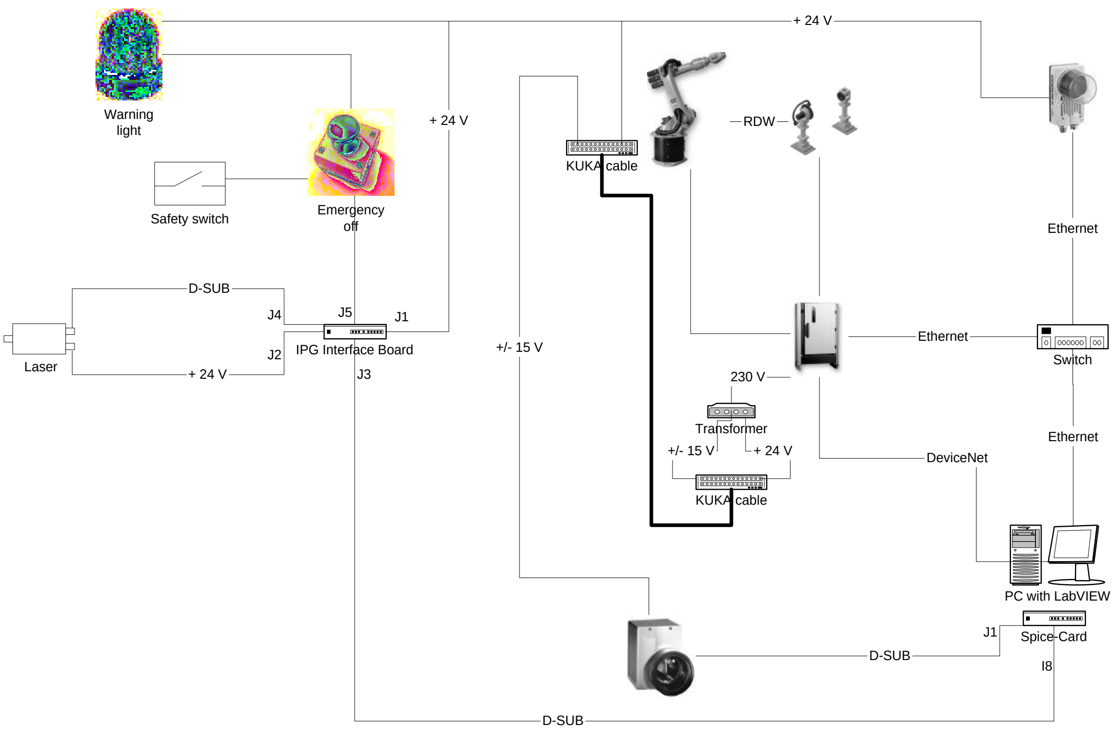


Figure 43: Cable connections between single components

10. Automatic External mode

If robot processes have to be controlled by a central station, for example by a main computer or by a SPC, it has to occur in the robot mode "Automatic External". The superordinate controller transmits the signals to the robot for processes like *motion enable*, *fault acknowledgment*, *program start* etc. On the other hand, the robot control transmits information to the superordinate controller about operation and fault states.[19]

10.1. Definition of the I/Os

As the whole communication runs over DeviceNet, the signals are translated in digital I/Os, which need to be properly defined. KUKA has already defined some I/Os in collaboration with the automobile industry, but for clearly arranged programming, the widespread I/Os were grouped in the lower numerical range.

10.1.1. Robot inputs

The 17 robot inputs, which are at the same time the outputs of LabVIEW, as well as some system variables, are listed in the following tables:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
motion enable	fault acknowledgment	read program number	bit 1 of program number	bit 2 of program number	bit 3 of program number	bit 4 of program number	bit 5 of program number	bit 6 of program number	bit 7 of program number	bit 8 of program number	parity bit for program number	drives on	drives off	external start	activate I/O-interface	Camera-Bit

Table 7: Robot inputs

[19] KUKA – course of studies

	Value	Name	Type	Description
program number	1	PGNO_TYPE	Variable	Determines which kind of format the robot expects from the superordinate controller. The value 1 corresponds to binary coded.
	0	REFLECT_PROG_NR	Variable	Defines whether the program number should be mirrored on a settable output.
	8	PGNO_LENGTH	Variable	Defines the number of bits communicated by the superordinate controller.
	4	PGNO_FBIT	Input	Input channel which displays the first bit of the program number.
	12	PGNO_PARITY	Input	Parity bit of the program number (signal set = even parity)
	3	PGNO_VALID	Input	Input channel which transmits the command to read in the program number with the rising flank.
robot movements	15	$EXT_START	Input	Starts or resumes a program with the rising flank.
	1	$MOVE_ENABLE	Input	If set, the robot can move.
	TRUE	$CHCK_MOVENA	Variable	Monitoring for $MOVE_ENABLE is operative. Settable in OPTION.DAT.

	2	$CONF_MESS	Input	Fault acknowledgment
miscellaneous	13	DRIVES_ON	Input	Superordinate controller can switch on robot drives by sending a high-impulse of at least 20 ms duration.
	14	DRIVES_OFF	Input	Superordinate controller can switch off robot drives by sending a low-impulse of at least 20 ms duration.
	16	$I_O_ACT	Input	Activates the I/O-interface.
	17	Camera-Bit	Input	User defined input in order to trigger the camera check process.

Table 8: Description of robot inputs

10.1.2. Robot outputs

The 30 robot outputs which are transmitted in four bytes are shown below:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
ext. & int. emergency-off-circuit closed	drives ready	aut. ext. interface ready	STOP-message available	operator safety	process/interrupt active	request program number	robot justified	program running	robot moving	robot stopped	robot in HOME position	robot on path	robot near path	T1 mode	T2 mode

17	18	19	20	21	22	23	24	25	26	27	28	29	30
automatic mode	automatic external mode	control ready	internal emergency-off-circuit closed	bit 1 of reflected prog. nr.	bit 2 of reflected prog. nr.	bit 3 of reflected prog. nr.	bit 4 of reflected prog. nr.	bit 5 of reflected prog. nr.	bit 6 of reflected prog. nr.	bit 7 of reflected prog. nr.	bit 8 of reflected prog. nr.	Laser-Bit	NextJob-Bit

Table 9: Robot outputs

	Value	Name	Type	Description
starting conditions	19	RC_RDY1	Output	Ready for program start
	1	ALARM_STOP	Output	Set if the external and internal emergency-off-circuit is closed.
	5	USER_SAF	Output	Operator-safety-circuit closed (e.g. protective grid).
	2	PERI_RDY	Output	Robot drives ready.
	8	ROB_CAL	Output	Robot is justified.
	3	I_O_ACTCONF	Output	The automatic external interface is active. The signal switches to TRUE as soon as the mode is set to EXT.
	4	STOPMESS	Output	Used to inform the superordinate controller about a message which stopped the robot.

	21	PGNO_FBIT_REFL	Output	First bit for reflected program number (see variable REFLECT_PROG_NR).
	20	Int. NotAus	Output	Set if internal emergency-off-circuit is closed (pushbutton on KCP).
program state	6	$PRO_ACT	Output	Set if a process or interrupt is active.
	7	PGNO_REQ	Output	Signal change requests a program number from the superordinate controller.
	9	APPL_RUN	Output	Set if (sub-)program is being executed.
	10	PRO_MOVE	Output	Robot is on the move (at least one synchronic axis ranges).
robot position	11	ROB_STOPPED	Output	Robot is not on the move (Negation of PRO_MOVE).
	12	IN_HOME	Output	Robot is in his HOME position.
	13	ON_PATH	Output	Robot is located on his path.
	14	NEAR_POSRET	Output	Robot is near his path (in an orb around the position saved in $POS_RET).
operating mode	15	T1	Output	Set if robot is in T1 mode.
	16	T2	Output	Set if robot is in T2 mode.
	17	AUT	Output	Set if robot is in automatic mode.
	18	EXT	Output	Set if robot is in automatic extern mode.

external control	29	StartLaser	Output	User defined output to start laser process.
	30	NextJob	Output	User defined output to increment the job number.

Table 10: Description of robot outputs

KUKA also brings the possibility to transmit fault numbers in the range of 1 to 255 to the subordinate controller. This could for example be useful in case a wrong program number is transmitted. If PGNO_PARITY does not corresponds to a program number, the default program in *cell.src* is started. If a program number is transmitted that does not exist, the robot stops with the corresponding fault number. Sending this fault number back to the subordinate controller, which matches the number to an adequate message, could help with the analysis of errors.

10.2. Communication processes[20]

The definition of the I/Os leads us to the next step, which is the controlled interaction between the robot and the superordinate controller. It is then necessary to preestablish communication between those two devices with a handshake.

The following signal diagrams show different use cases and define the reaction of the soft SPC, which is in the engraving system LabVIEW.

[20] KUKA – course booklet for advanced training

10.2.1. Prime Handshake

Automatic system start and normal operation with program number acknowledgment by means of PGNO_VALID.

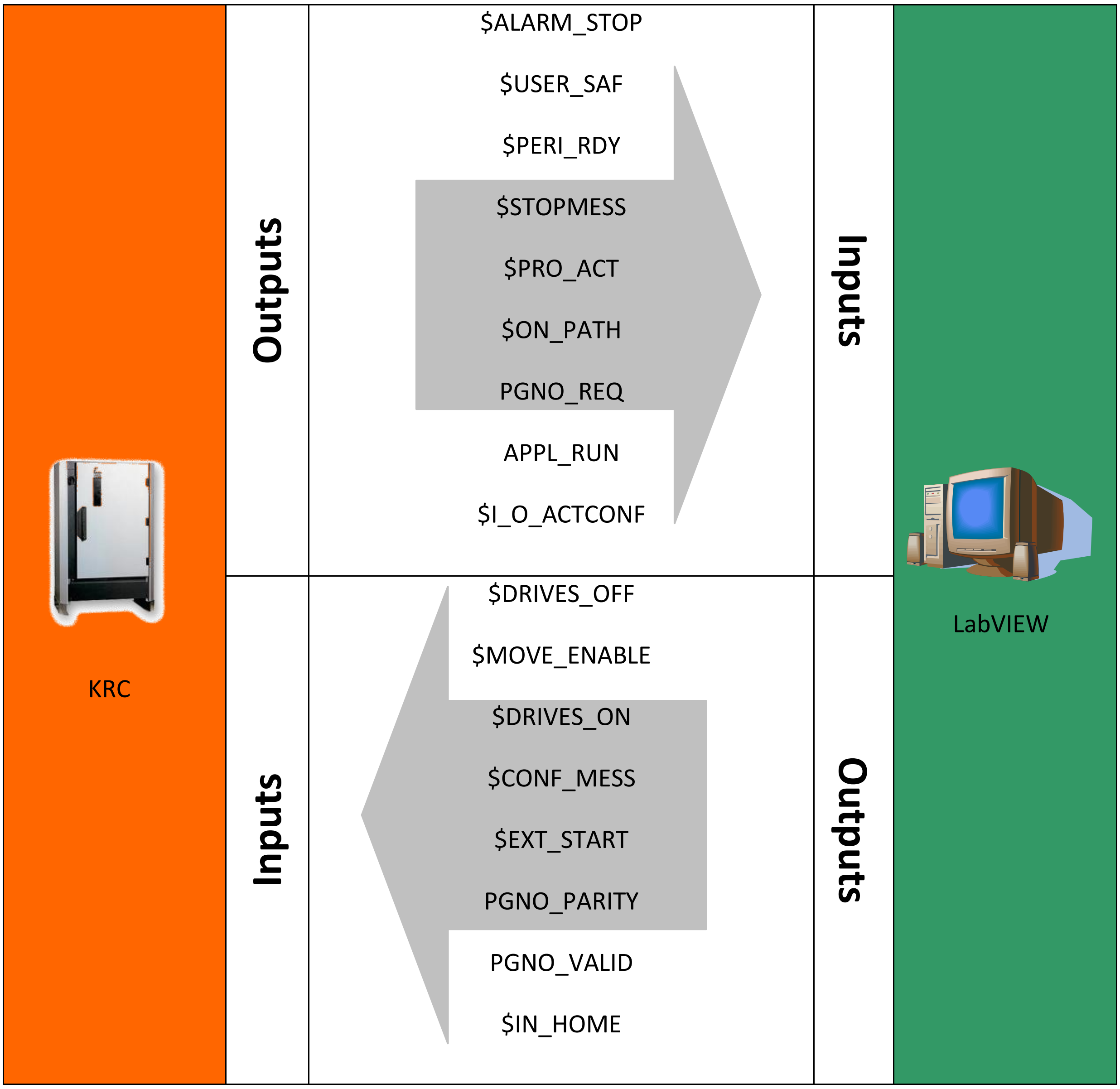


Figure 44: I/Os of robot

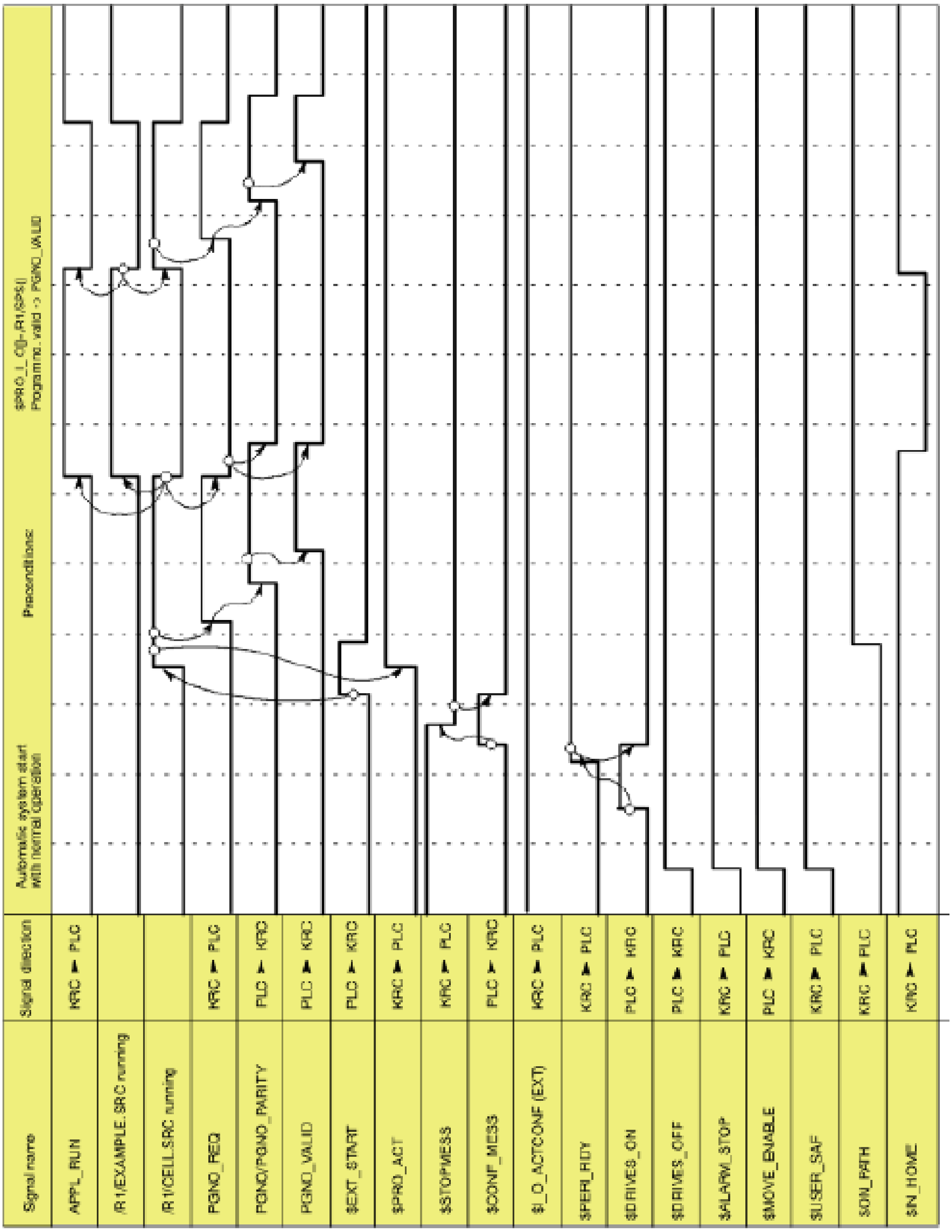


Figure 45: Automatic system start by means of PGNO_VALID

10.2.2. Restart after dynamic braking

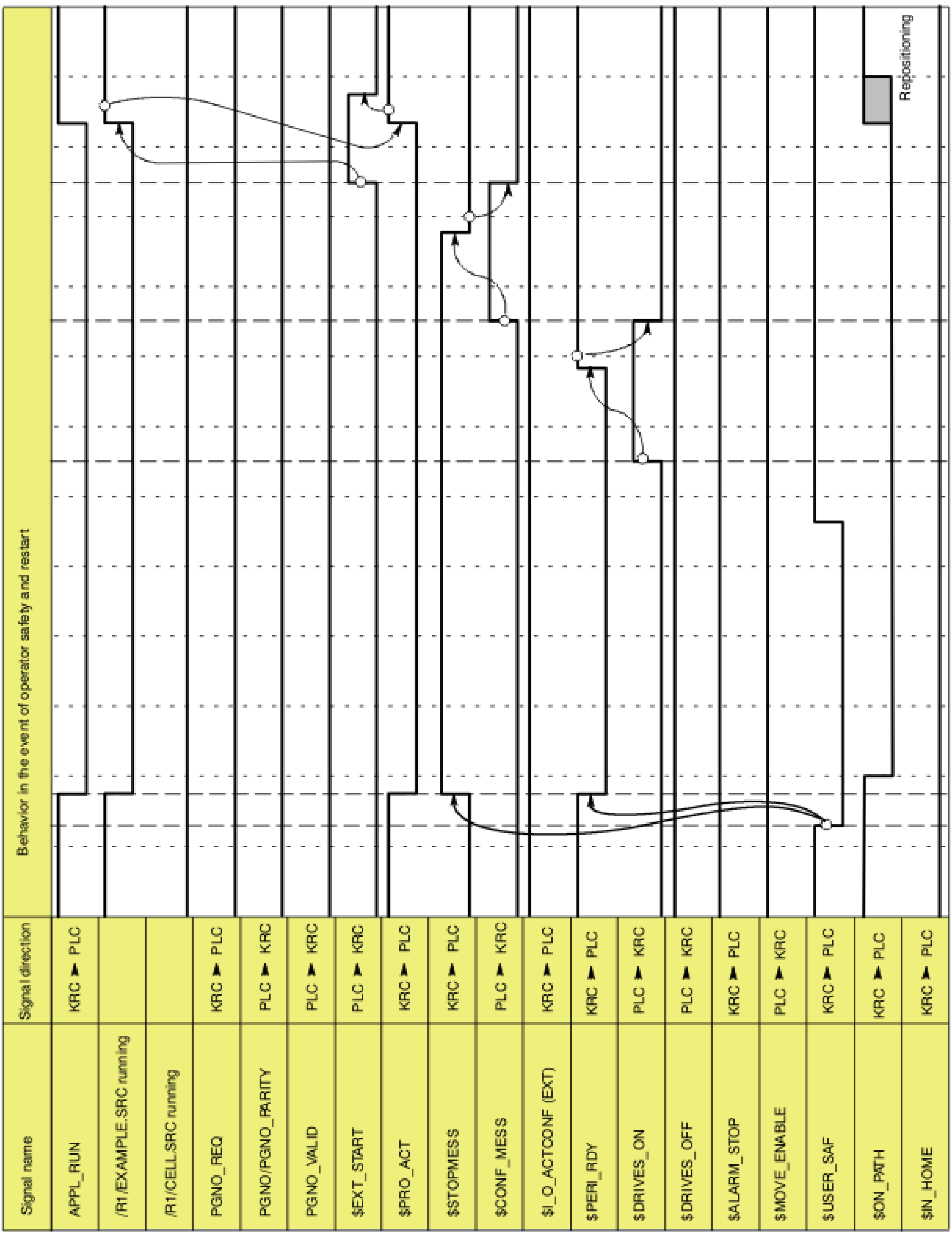


Figure 46: Restart after dynamic braking (operator safety and restart)

10.2.3. Restart after emergency stop

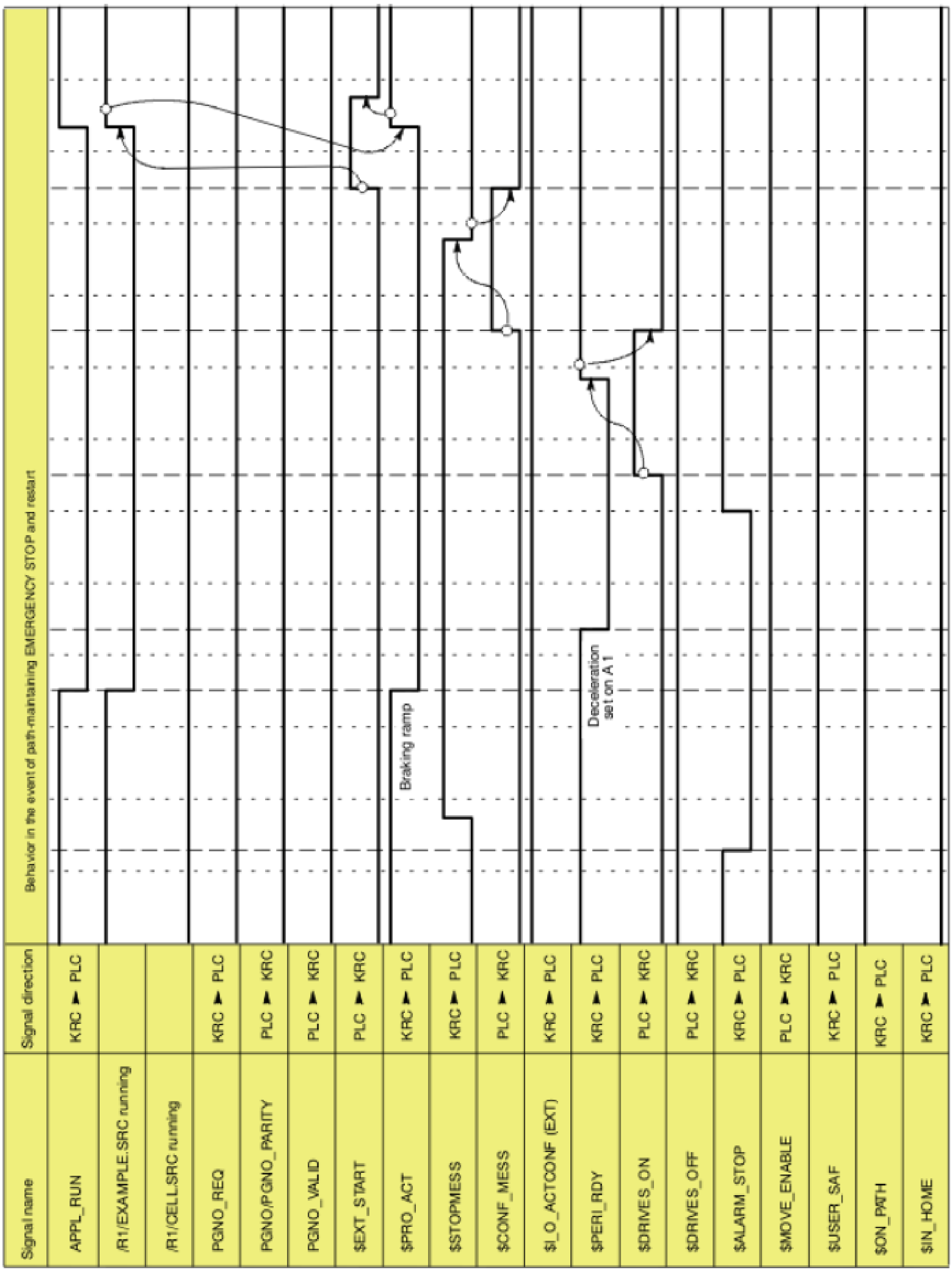


Figure 47: Restart after path-maintaining emergency stop

10.2.4. Restart after motion enable

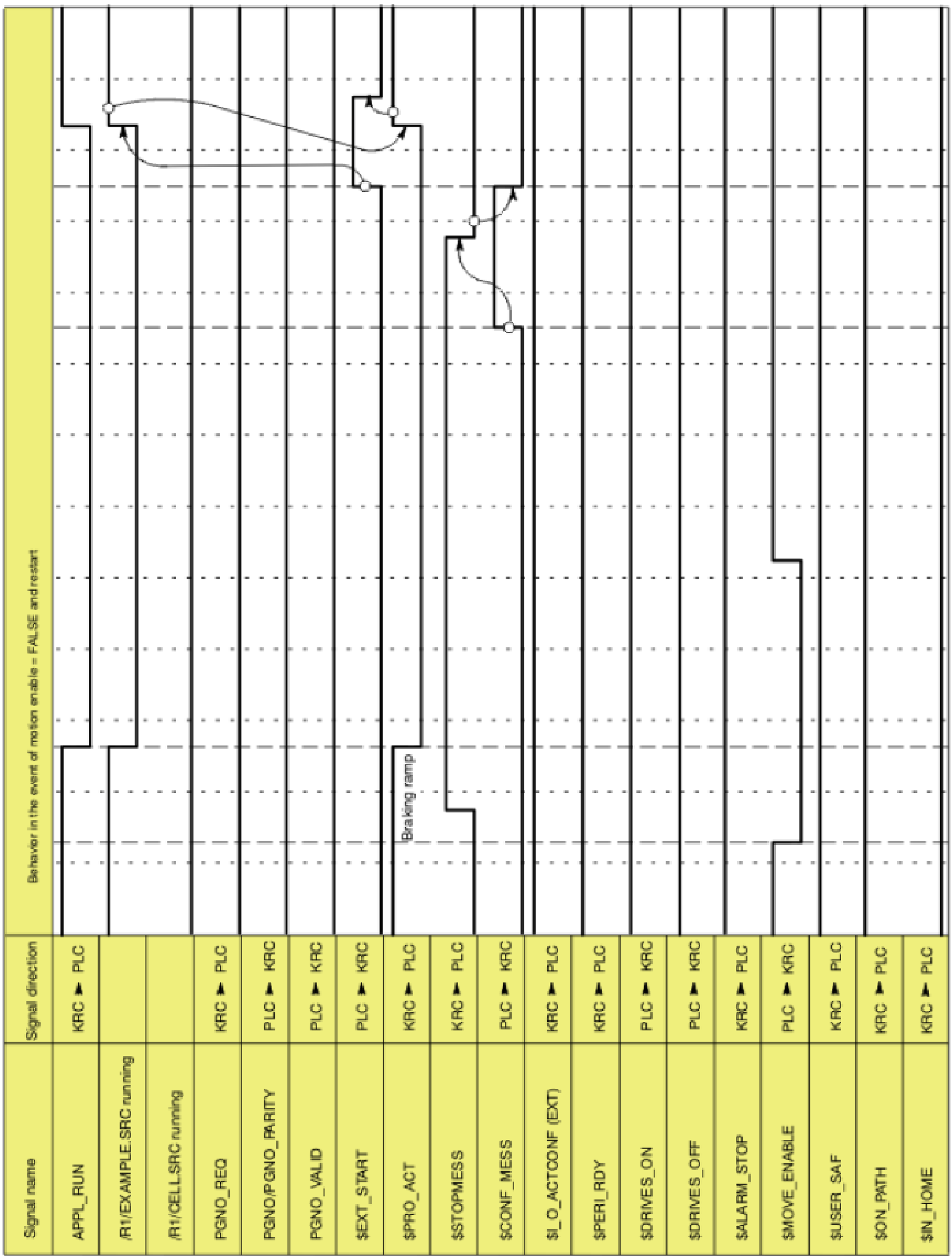


Figure 48: Restart after motion enable

10.2.5. Restart after user STOP

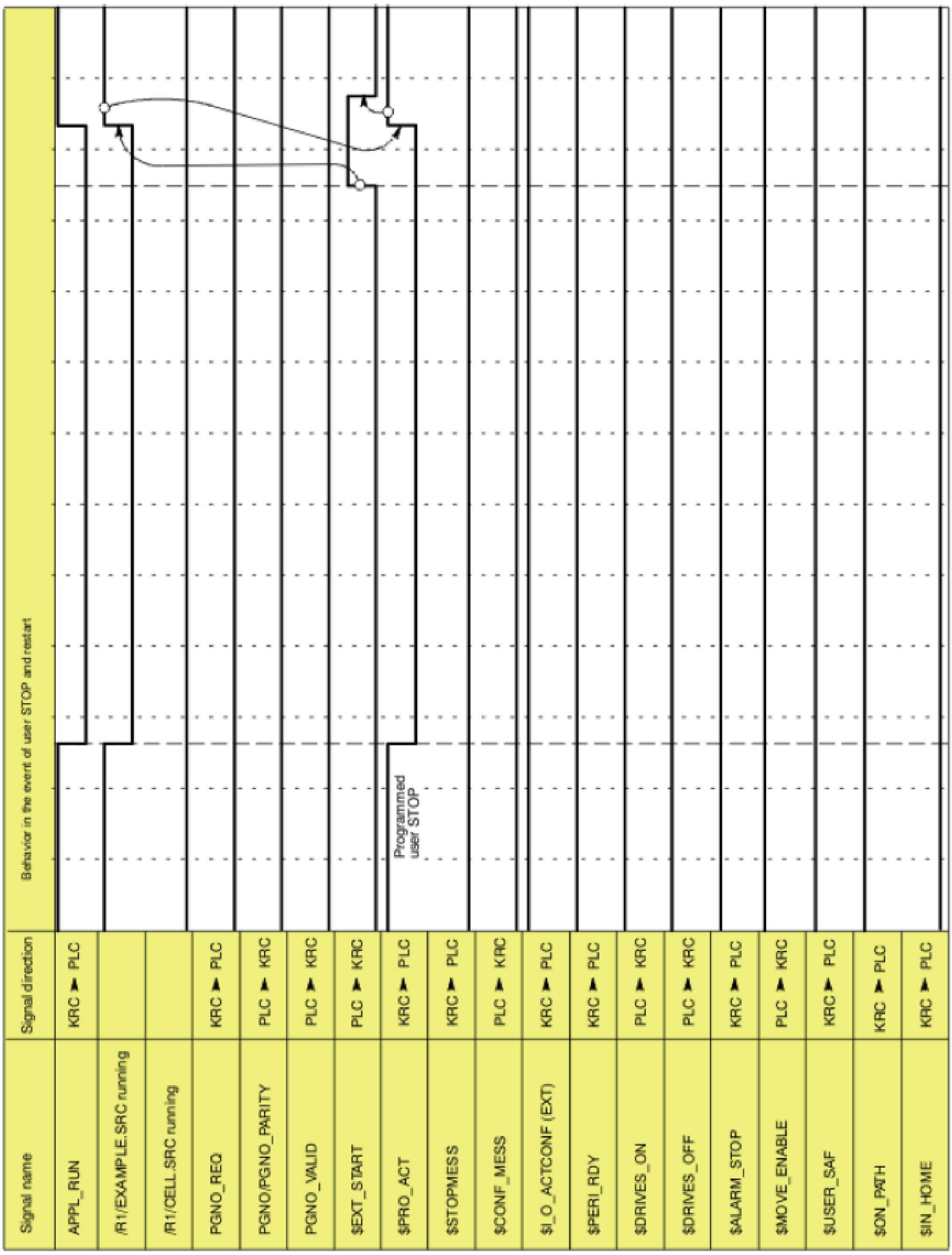


Figure 49: Restart after user STOP

11. Safety

Running the KR-16 in Automatic External mode includes high velocities and accelerations. Because the cell is primarily the working space for the robot, it could be dangerous for a human being to stay in the cell. Furthermore using a laser of class 4 entails special precautions for safe operation. Therefore, several safety precautions for the engraving system are listed below.

11.1. Hardware Safety

Hardware Safety means that despite short circuits, hardware damages or software implementation mistakes, the system still behaves as programmed. This can be realised, for example, by using relays which are not dependant on the software or by doubly securing a crucial circuit and therefore, obtaining a redundancy.
Usually in this case, a SPC is employed, but for the few critical circuits in the engraving system, the robot control can undertake the task of safety control because KUKA provides by default safe electrical circuits.

The main application which needs to be safe is the immediate shut down of the laser and the robot if somebody enters the cell. Therefore, a switch has been fixed at the door which is connected to the safe channels 7 and 25 of the robot (see Figure 49). Another important application is the connection of the emergency stop buttons in- and outside the cell. As the operator has to get into the cell to change the launch tubes and clamp them in the turnover positioner, an accident could happen and therefore an emergency stop button inside the cell is indispensable. The same applies if the operator is standing outside and notices that the launch tube is not fixed properly in the turnover positioner anymore.

In order to prevent an external person entering the cell while the engraving system is running, a signal lamp is fixed outside the cell. This lamp flashes once the robot's drives are set to ON.

The safety cabling is fixed at the robot over the X11-connector using a Harting-plug with pin inserts:

external EMERGENCY-OFF-channel A +		1
local EMERGENCY-OFF-channel A		2
local EMERGENCY-OFF-channel A		3
external EMERGENCY-OFF-channel A -		4
test output A		5
approval channel A		6
EMERGENCY-OFF A	Door switch	7
protection device channel A		8
EMERGENCY_OFF B		25
protection device channel B		26
drives ON A	Laser approval	11
drives ON A		12
0 V (signal lamp –)		18
external EMERGENCY-OFF-channel B +		19
local EMERGENCY-OFF-channel B		20
local EMERGENCY-OFF-channel B		21
external EMERGENCY-OFF-channel B -		22
test output B		23
approval channel B		24
drives ON B		29
drives ON B (signal lamp +)		30
24 V +		36
test output A		38
test output B		39
test output channel A		41
external drives OFF		42
qualifying input A		50
qualifying input B		51
+VCC external		88
GND external		89
+24 V internal		106
0 V internal		107

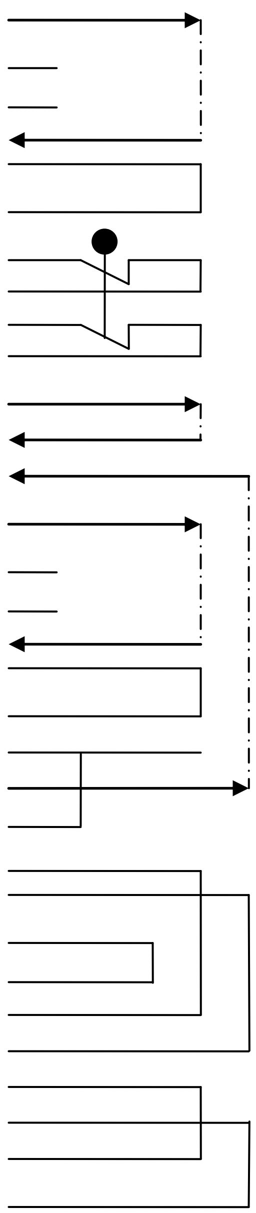


Figure 50: X11 connector for safety

11.2. Software Safety

Beside the Hardware Safety, the Software Safety exists as well. This is the interception of fault cases by a program. In LabVIEW, the state-machine checks the input data with the subVI *CheckExternalEvents.vi* (see Figure 40 left side outside the loop) in regular intervals. If for example the door has been opened, the robot's output number 5 corresponding to *USER_SAF* is set to 0. For this reason, the state-machine is forced in the state *wait_user_saf_T* (see Figure 50). The state-machine restarts the system like specified in the signal diagram after dynamic braking (see Figure 45).

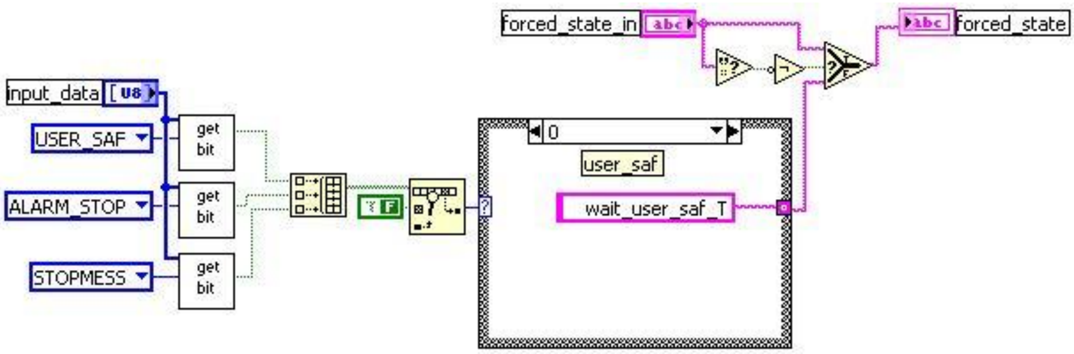
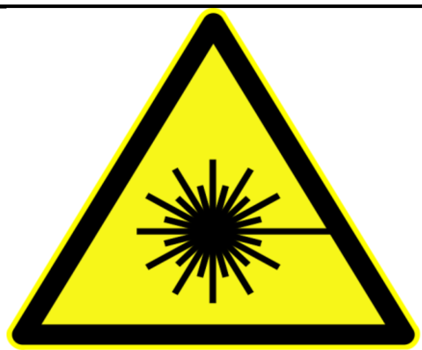


Figure 51: Checking of safety signals

11.3. Warning sings[21]

Using a laser of class 4 entails the placing of several signs. These signs warn the personnel of the dangers which could occur while the laser is running. Those signs have to be fixed outside the cell and directly on the laser.

- international laser warning sign - must be fixed on the door to the cell and on the laser	

[21] BGV - Unfallverhütungsvorschrift

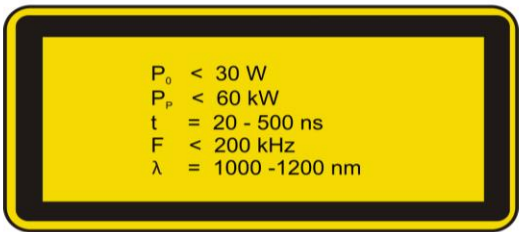
- warning label with lasers classification and the behavioural rule	
- exact specification of the lasers properties - must be fixed outside the cell and on the laser	

Table 11: Warning signs and their significations

11.4. Further safety precautions

During the installation and the testing of the laser, it is mandatory to wear special protection glasses which can protect the eyes during exposure to a direct laser beam with a wavelength of 1064nm for up to 10 seconds. The contact with the direct laser beam is, of course, quite detrimental because the beam runs through the human skin and flesh and attacks the bones. One should also be careful of the reflected laser beam (see Figure 31). Especially on a bended working surface, the reflection angle can become quite big and attain each point in the cell. Therefore long working clothes are recommended.

Besides the concrete safety precautions a laser instruction should not be missed. In this instruction, the different laser classes are discussed, as well as the correct registration at the consortium. Furthermore, the right behaviour in the event of an accident is explained.

11.5. Test sequences

For a proper system implementation, well-defined test sequences should not be missed. Those tests must be worked out by person other than the system builder in order to assure no error in reasoning is done twice. Regrettably, the test sequences would go beyond the scope of this thesis and are mentioned here for the sake of completeness.

12. Conclusion

Within the scope of this bachelor's thesis, all the tasks required have been fulfilled. The additional functions could not be implemented due to the highly limited research time of only four months. The complete engraving of the PARS launch tube with all the final symbols is not possible because the cell has not yet been constructed.

A particular challenging part of the thesis was the realisation of the communication between LabVIEW and the robot over DeviceNet. The concept appeared to be evident but the complexity of the problems lay in the details. One problem was the proper configuration of the LPDN-Scanner-card in the robot control. After several phone calls with KUKA, mails containing the robot's configuration and reams of searches in the Internet, the robot could finally establish a connection with LabVIEW. Another difficulty was that the robot works with the definition of big endian, LabVIEW however with little endian. In this case, several searches had to be done before the problem could be localised. The last major problem, however, occured with the use of Robot VisionCom as a beta software. Some bugs were found although only problems in the personal implementation of the KRL-program were anticipated. Contact with KUKA provided clarity in those cases as well.

As a new release of VisionCom has appeared only at the end of the thesis, it could not be installed on the robot's control. This upgrade, as well as the implementation of the tasks mentioned in the requirements, are going to be done during the months following this Bachelor's thesis. Furthermore, a touchpannel from Beckhoff with several hardware buttons, including an emergency stop button, will be embedded in the engraving system.

13. Index of literature

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14. Index of figures

15. Index of tables

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