Abstract—Robotic laser welding imposes high demands on the accuracy of the laser focal point with respect to the joint to be welded. Sensors measuring close to the laser focal point are therefore required to make robotic laser welding successful in a production environment. Because of the high accuracy requirements, even small imperfections in the system can have a bad influence on the resulting accuracy during welding. This paper gives a general framework of the coordinate frames that occur in a sensor-guided robotic laser welding cell. A simulation environment of the process of teaching seam locations with the use of a seam tracking sensor is developed. With such simulations the influence of position and orientation errors in the laser tool frame and sensor tool frame can be visualized. Furthermore the influence of errors in the kinematic model of the robot controller is shown. The knowledge obtained with these simulations gives insight for the development of more intelligent seam teaching algorithms that minimize these influences.

I. INTRODUCTION

Programming the robot for laser welding is a time-consuming task, especially if complex 3D seams have to be welded. Because laser welding puts high accuracy requirements on the final position of the laser beam with respect to the weld joint, seam-tracking sensors are required for complex welding tasks [1].

In general two strategies can be distinguished for sensor-guided robotic-welding:

- Teaching of seam locations with the sensor in a first step (seam teaching), laser welding in a second step.
- Real-time seam tracking and laser welding. If the sensor is mounted some distance in front of the laser beam it can be used to correct the welding trajectory during welding.

In a production environment the second method would probably be preferred as it makes the separate step of teaching the seam locations in a product obsolete, and thus saves time and money. Nowadays real-time seam tracking and laser welding is therefore mainly applied for large product series, e.g. automotive. Seam teaching has the advantage that the velocity is not prescribed by the welding process. Therefore it can be done at a low speed, or in small steps where the robot is stabilized after every step. This increases the accuracy as dynamic robot behavior and synchronization errors between robot joint measurement and sensor image acquisition can now be avoided. Seam teaching is mainly applied for small product series, where both manual and sensor-guided teaching are used.

Seam teaching for arc welding has been regarded as being solved by many authors, see e.g. [2]. They therefore mainly focus on ways to use sensor information for real-time seam-tracking. The accuracy requirements for laser welding however give a different perspective to seam teaching. The resulting accuracy of the laser focal point with respect to the joint to be welded depends on the weld type and material to be welded, but may have to be better than 100 \( \mu \text{m} \). Such accuracy requirements come close to the maximum that can be obtained by commonly used 6-axes industrial robots. Many effects (robot kinematics, errors in transformations) that were previously not playing a big role now can’t be left without attention. The integration of a seam-tracking sensor in a robotic laser welding cell for teaching is therefore not straightforward.

To illustrate the resulting accuracy during welding an experiment was carried out in which a seam-tracking sensor made by Falldorf GmbH was mounted on two different locations on the flange of a Stäubli RX90 robot, 55 mm apart. A sine-shaped trajectory (fig. 1) was taught (by making point-to-point movements) with the sensor mounted on the first mounting location. After teaching, the sensor was mounted on the second mounting location (which represents the laser tool). The taught locations were now replayed (again by moving from point-to-point) using a different tool definition in the robot controller. The sensor was used to measure the positional accuracy \( S_y \) perpendicular to the welding direction and the orientation \( S_\rho \) in the welding direction. The results are shown in fig. 1.
waggles over the trajectory during teaching, which causes the fluctuating orientation $S^p$.

The following factors may be of influence:

- Sensor errors (measurement noise, pixel resolution, etc)
- Positional errors in the sensor and laser tool transformations
- Orientation errors in the sensor and laser tool transformations
- Errors in the used nominal kinematic robot model (in the controller)

According to the authors, a clear overview of the influence of these errors on the welding accuracy does not exist. Furthermore, these errors all occur simultaneously on the experimental setup. It is not possible to see the influence of the above factors separately, which makes it impossible to point out the main cause of errors. Therefore a simulation environment has been developed, where separate errors can be switched on, while the remaining system stays ideal. This papers shows how the different components existing in a seam teaching process can be modeled. These include the robot with its controller, the seam-tracking sensor, the teaching algorithm that is used and a model of the seam to be welded. It will be shown that the seam teaching process can be investigated successfully with such a simulation environment.

II. COORDINATE FRAMES

To describe the position and orientation of points or bodies with respect to each other a coordinate system or frame is usually attached to each body. A transformation describes the location (position and orientation) of a frame with respect to a reference frame. A common way to mathematically describe a transformation is by using a homogeneous transformation matrix [3], which is also the convention used in this work. An overview of the different frames and transformations that can be distinguished in a sensor-guided robotic welding system can be found in [2]. This overview is extended in this paper, by adding a Station frame $T$ and a Product frame $P$ (fig. 2).

Fig. 2. FRAMES IN A SENSOR-GUIDED ROBOTIC WELDING SYSTEM

Frames are indicated by a capital. Transformations are indicated by the symbol $T$ with a leading superscript, that defines the reference frame they refer to. The leading subscript defines the frame they describe. The following frames can be distinguished:

- Base frame $B$. This frame is attached to the robot base. It is used as a reference frame and does not move with respect to the environment.
- Null frame $N$. The Null tool is located at the end of the robot flange. The Null frame is described with respect to the Base frame by coordinate transformation $B^N_T$, which is a function of the values of the joint angles of the robot arm (forward kinematics).
- Laser tool frame $L$. The Laser tool is located at the Tool Center Point of the laser beam, where the z-axis coincides with the laser beam axis. Because the laser beam is axi-symmetric, the direction of the x-axis is arbitrary. It will be chosen in the direction of the Sensor tool. The transformation $N^L_T$ describes the laser tool frame with respect to the Null tool frame. This is a fixed transformation determined by the geometry of the welding head.
- Sensor tool frame $S$. The sensor tool is fixed to the welding head and therefore indirectly to the robot flange. The transformation $S^L_T$ describes the sensor tool frame with respect to the Null frame. Note that this transformation can also be described with respect to the laser tool frame instead of the null tool, because both transformations are fixed.
- Station frame $T$. The station frame is the base of the station or work table a product is attached to. It is possible that the product is clamped on a manipulator which moves the product with respect to the base frame. In that case the transformation $B^T_T$ describes the station frame with respect to the base frame and depends on the joint values of the manipulator (forward kinematics). If no manipulator is present this transformation can be chosen as unity.
- Product frame $P$. The product frame is located somewhere on a product. The transformation $P^T_T$ describes the product frame with respect to the station frame. This frame is useful if a series of similar products is welded on different locations of a station.
- Seam frames $C_i$. Every discrete point on a seam can be described with a different coordinate frame, which is the reason the index $i$ is used. The transformation $P^C^iT$ describes seam frame $i$ with respect to the product frame.

In many cases (like our laboratory setup) an external manipulator is not present and a series of products will only be welded at the same location in the work cell. Both $B^T_T$ and $P^T_T$ can then be chosen as unity. A seam frame $C_i$ is then described with respect to the robot base with transformation $B^C^iT$.

III. THE SEAM TEACHING PROCESS

In this section an overview of the seam teaching process is given, before the separate parts existing in such a system can be modeled. A schematic view of such a system is given in fig. 3.
The sensor and the welding head are both attached to the robot flange. They will be moved to a new location by the robot when the desired tool location $T_d$ is communicated to the robot controller. Information like the current location $T_c$ of the sensor or laser focal point can be obtained from the controller. The teaching algorithm is used to direct the sensor over the seam trajectory. It uses the current sensor position $T_c$, obtained from the controller, and the measurements $S_m$, from the seam tracking sensor to calculate a seam location $C_i$, which is recorded in a buffer for later use during welding. Furthermore it corrects the orientation and calculates a new desired tool location for the robot, which allows the sensor to teach curved seam trajectories. The sensor may be moved forward and backward along the trajectory with a variable step size for teaching of seams with very small radii of curvature.

### IV. SIMULATION ENVIRONMENT

The goal of the simulation environment is to provide a realistic description of how the actual seam teaching process works. The simulations obtained with it should give a good representation of the effects that also occur in practice.

A block diagram of the simulation environment is shown in fig. 4. The structure is similar to fig. 3, but now the actual robot and sensor are replaced with blocks as they will be modeled as well. Note that although the seam trajectory is not visible in the block diagram, it also needs to be modeled. The sensor model uses both the actual sensor location $T_d$ and a model of the seam trajectory to calculate the sensor values $S_m$.

### Seam model

A real seam trajectory consists of the edges of the metal plates that have to be welded. The surface normal of the workpiece at some point of the seam trajectory determines the orientation of the seam at that point. The seam to be welded can be seen as a continuous trajectory that is located somewhere in 3D space, as determined by the location of the product to be welded within the robot workspace. The focal point of the laser beam should track this trajectory as good as possible during welding to produce a good weld. From a mathematical point of view, the position of a discrete point $i$ on the seam trajectory can be described by a vector $P_i$. The orientation of the laser beam is also important during welding, therefore the modeled seam trajectory should also have a sense of orientation. The orientation of such a point is described by surface normal $n_i$. Note that a single point on a seam does not provide information about the direction of the seam trajectory. Direction can be derived only if at least 2 points (and their order) are known.

The seam model can be defined by choosing a number of discrete points on the seam trajectory that consist of a position vector and a surface normal. In a product however, the trajectory has a continuous nature. Therefore the seam trajectory should be interpolated between the discrete base points. A segment-wise cubic parametric spline of the form

$$K_i(\lambda) = \begin{bmatrix} P_i(\lambda) \\ n_i(\lambda) \end{bmatrix} = a\lambda^3 + b\lambda^2 + c\lambda + d,$$

is chosen as the interpolation function, where $P_i(\lambda)$ represents the position vector and $n_i(\lambda)$ the surface normal. Given a spline segment $i$ between $K_i$ and $K_{i+1}$ as shown in fig. 5, four surrounding base points are needed to calculate the spline coefficients $a$, $b$, $c$ and $d$. The coefficients on the segment are calculated with the Catmull-Rom [4] method as

$$\begin{bmatrix} a^T \\ b^T \\ c^T \\ d^T \end{bmatrix} = \begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 3 & 0 & 0 \\ 1 & -2 & 1 & 0 \end{bmatrix} \begin{bmatrix} K_{i-1}^T \\ K_{i}^T \\ K_{i+1}^T \\ K_{i+2}^T \end{bmatrix}.$$  

The spline-functions exist between the start of segment $i$ at $\lambda = 0$ (where $P_i(0) = P_i$ and $n_i(0) = n_i$) and the end of the segment at $\lambda = 1$ (where $P_i(1) = P_{i+1}$ and $n_i(1) = n_{i+1}$). An advantage of the cubic spline is that it can be used to accurately interpolate complex trajectories with only a small number of base points. Another useful property of the spline is its smoothness, because the first derivative of the interpolation function is continuous.

**Sensor model**

One of the most important parts in a seam teaching system is the seam-tracking sensor. There are several underlying physical principles for seam-tracking sensors [2]. The sensor based on optical triangulation shown in fig. 6 is used most often. It is also the sensor type used in our experimental setup.

A laser diode is used to project a line of light onto a surface. A camera looks at the diffuse reflection of the light on the
surface under a different angle $\alpha$ from the angle of incidence. From the camera image many features of the weld joint can be extracted. It gives information on four degrees-of-freedom, namely 3 positions and 1 angle. Furthermore it offers the possibility to use it for real-time seam-tracking during laser welding by choosing an appropriate optical filter.

The sensor uses a camera to look at the intersection $^S I$ of the seam trajectory with the laser diode plane $D$. The 3D coordinates of the intersection are projected on the 2D camera. Using the known diode angle $\alpha$ the coordinates of the intersection can be calculated from the camera coordinates. The origin of the sensor frame $S$ is defined to be in the middle of the camera image on the laser diode plane. The sensor calculates the position of the intersection $^S I$ with respect to its coordinate frame $S$. A mathematical model of the sensor should therefore at least consist of the calculation of an intersection of the spline function of eq. [1] with the laser diode plane.

Suppose that both the current Sensor location $^P S T$ and the positional part of the interpolated seam model $^P P_i(\lambda)$ are known with respect to the product frame $P$. The positional part of the seam model can then be expressed with respect to the sensor laser diode plane $D$ as

$$^D P_i(\lambda) = ^P S T^{-1} \cdot R_y(90^\circ - \alpha)^{-1} \cdot ^P P_i(\lambda), \quad (3)$$

if the $z$-axis is taken normal to the laser diode plane and $R_y$ is the homogenous transformation corresponding to a rotation around the $y$-axis. Because eq. [1] easily provides derivatives of the spline functions an iterative Newton-method is used to quickly find the value of $\lambda_{sol}$ on the segment $i$ for which the $z$-position of eq. [3] has a zero-crossing. The sensor then returns the coordinates of the intersection $I$ with respect to frame $S$, which are found as

$$\begin{bmatrix} ^S x_i \\ ^S y_i \\ ^S z_i \end{bmatrix} = ^P S T^{-1} \cdot ^P P_i(\lambda_{sol}). \quad (4)$$

Beside the joint coordinates, the seam-tracking sensor also calculates an orientation angle $^S \rho$. This orientation angle is defined as the angle of the intersection between the workpiece plane and the laser diode plane, in the $xy$-plane of the sensor as this is the plane as it is seen by the camera. Because the value of $\lambda_{sol}$ is derived before, the surface normal of the seam trajectory at the intersection is already known. The vector $^S I$ that represents the intersection line with respect to the sensor frame is found as the cross-product

$$^S I = ^P S T^{-1} \cdot (\frac{\partial}{\partial \lambda} n \cdot R_y(90^\circ - \alpha)) \times ^P S n_i(\lambda_{sol}), \quad (5)$$

and the orientation angle $\rho$ is found from it as

$$^S \rho = \arctan 2(^S I_x, ^S I_y). \quad (6)$$

Robot model

The main task of the industrial robot controller is the basic function of controlling the tip movement. A block diagram is shown in fig. 7. A desired tool location $^N T_d$ is first translated to the required tool location $^N N_d$ of the robot flange, using the known transformation $^N T_c$. The nominal kinematic robot model that is present in the robot controller is used to calculate the desired joint angles $^N q_d$. Note that a solution does not necessarily exist, e.g. when the desired tool location is out of the robot workspace. Inside the robot workspace mostly multiple solutions exist, i.e. the same location can be reached with different robot arm configurations. The obtained joint angles $^N q_d$ are the reference input for a servo controller. This servo controller outputs motor currents $i$ and tracks the measured robot joint angles $^m q_m$ equal to the desired joint angles $^N q_d$.

The robot controller can be asked for the current location of the tool $^c T_c$. The measured joint angles $^m q_m$ are then used to calculate the location of the robot flange $^N N_c$ with the nominal forward kinematic model. The known transformation $^N T_c$ is then used to calculate the current tool location according to the robot controller.

In the previous block-diagram the components inside the robot controller are known, except for the servo controller part. In the case of seam teaching the robot makes point-to-point movements and then stabilizes. Therefore it would be valid to assume that $^m q_m$ is equal to $^N q_d$. To accurately predict the effect of kinematic errors in a sensor-guided robotic laser welding system, the actual kinematics should be modeled. Several parameters of a kinematic model can be adjusted to improve the robot model, e.g. arm lengths, encoder offset or link angles [5]. In order to describe the actual location $^c T_a$ of the sensor
The most significant influence on the accuracy during welding are using the simulation environment. The errors, which have shown. In the simulations, a nominal tool definition for the physical dimensions of the welding head and seam-tracking sensor. The look-ahead distance between the Sensor tool and Laser tool is chosen to be 55 mm. The tool axes are similar as in fig. 6 where the x-axis is the welding direction.

The modeled seam trajectory of fig. 1 is taught using the Sensor tool. The taught seam locations are replayed using a different tool transformation. During welding this would be the transformation of the laser focal point with respect to the robot flange. To simulate this behavior the sensor model is used at the laser location, so it can be used to simulate the accuracy of the laser focal point with respect to the seam trajectory. In the ideal case, where only quantization errors due to the limited pixel resolution in the sensor are switched on, this results in a perfect weld, without positional and orientation errors.

**Tool transformation errors**

This section shows the effect of errors in the different tool transformations of the tool with respect to the robot flange.

SENSOR TOOL TRANSFORMATION: The effect of a position error in the Sensor tool transformation is shown in fig. 8. The actual Sensor tool transformation \( S_T d \) deviates a distance of 0.5, -0.2 and 0.2mm in x, y, and z-direction of the Sensor tool definition \( N_T c \) in the robot controller.

![Fig. 8. POSITION ERROR IN SENSOR TOOL TRANSFORMATION](image)

It is shown that a position error has a direct influence on the positional accuracy during welding. Errors in different directions have a different effect. An error in the y-direction results in an offset of the \( S_y \) signal on straight segments (start and end of the seam trajectory). An error in the x-direction is only visible on non-straight segments, because during welding the robot moves the laser tool too early or too late when a corner arrives. At last an error in the z-axis results in an error in the focal position of the laser. Generally, the \( S_y \) error perpendicular to the seam trajectory has the biggest effect on the welding quality and must be small. Note that the measured welding accuracy of fig. 1 looks very similar to this figure, so probably the transformation between the two tools has a position error.

A position error does not have a noticeable effect on the orientation accuracy, which is as expected since the seam teaching algorithm only makes small relative movements.

Orientation errors don’t have a noticeable effect on both the position and orientation accuracy, which could be expected from the seam teaching algorithm as it only makes small relative movements. They have a small effect on the orientation accuracy however. This results in small oscillations in its values. These oscillations are associated with a waggling motion of the sensor during the teaching procedure. This waggling effect however is much smaller than can be observed
at the experimental setup (fig. [1]), which is the reason it is not plotted here.

**Laser tool transformation:** Errors in the position of the Laser tool have a similar effect on the accuracy as a positional Sensor tool error, because after a seam location is taught, the robot is moved to the wrong location during welding.

Errors in the orientation of the Laser tool result in a constant orientation offset of the laser beam during welding. They can’t have an effect on the waggling motion, because during teaching the location of the Laser tool is not used.

**Kinematic errors**

This section shows the effect of errors in the actual kinematics of the robot arm.

The average encoder offset error between the identified kinematic model and the nominal kinematic model in the robot controller is about 0.06 degrees, which already causes an absolute tip position error of almost 0.5 mm for a robot link length of 450 mm.

To investigate this, the simulation environment should be extended to include this effect.

Kinematic errors due to a robot movement have an effect that can’t be ignored for robotic laser welding. Kinematic errors in the order of a tenth of a millimeter can occur, even for a look-ahead distance as small as 55 mm. These errors can be too large for laser welding applications, where very accurate positioning is required.

To decrease the effect of the kinematic errors large robot joint movements should be avoided. This can be done by choosing tool definitions that are close to the robot flange. The physical dimensions of the welding head and sensor usually determine the minimal distance that can be chosen. Another possibility to minimize joint movements is by preventing the orientation of the tool definition to change too rapidly as even small orientation changes of the tool can cause a major movement of the robot joints.

A product frame **P** and an external manipulator (station frame **T**) are not used. With respect to kinematics, such a manipulator however behaves in a similar way as the robot arm. Therefore similar effects on the accuracy are expected as caused by the kinematic errors of the robot arm. If a product is taught and welded at different locations of a station, similar errors are expected as are caused by the different location of Laser frame **L** and Sensor frame **S**.

As explained in this paper the accuracy requirements for laser welding make sensor-guided robotic laser welding more difficult if compared to other robotic welding applications like arc welding. Seam teaching algorithms that were previously used are not sufficient anymore. The knowledge about the influence of all kind of errors that occur in a sensor-guided robotic laser welding system should be used to design more advanced algorithms that minimize the influence of these errors. The simulation environment that is developed in this work proves to be very useful for testing and development of such algorithms.

**VI. Conclusions and Recommendations**

From the results in the previous sections several conclusions can be drawn. These will be discussed in this section.

A position error between the Laser and Sensor tool has a direct effect on the accuracy as it results in an offset during welding. A position error between the tools in y-direction results in an offset perpendicular to the seam trajectory. A position error in x-direction has an effect on the start and stop locations of the weld and has a bigger effect at locations when the seam trajectory has a smaller radius of curvature. An error in z-direction results in an offset of the height of the laser focal point. It is therefore very important to calibrate this transformation very accurately (better than 50μm) to make robotic laser welding successful [1].

Orientation errors in the Sensor tool result in a waggling motion. In simulation this waggling effect is much smaller than can be observed on the experimental setup. It is expected that non-linearities in the robot kinematics may play a role.

![Encoder Offset Error](image)

**Fig. 9. Encoder Offset Error**

In fig. 9 the position accuracy is shown to be badly influenced by encoder offset errors in the kinematic robot model. The resulting position errors are about 0.1 mm, which could already be too much for some laser welding applications. The biggest orientation errors occur at seam locations where the robot has to make the largest joint movements.

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