Automatic Generation of Safety Fields
for Articulated Construction Vehicle Arms

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Abstract. The Robotics Research Lab in Kaiserslautern pursues the goal of automating a mobile bucket excavator for excavation and loading tasks. Besides the functional requirements, safety is of utmost importance. This work presents an approach which simplifies the generation of laser-based safety fields for complex articulated robotic arms to prevent any damage or harm during panning movements. The technique is inspired by modern safety approaches that are common in production halls and extends them to cover more complex areas of application. The presented approach generates a predefined amount of safety fields which cover the configuration space of an articulated arm as closely as possible while keeping the complexity of the safety fields low for easier input and processing.

1 Introduction

Automating processes using increasingly complex machines slowly but surely finds its way into agricultural and construction domains. Simple applications like following a pre-defined trajectory are made possible through commercially available add-on systems. But of course, safety is a huge issue in the field of autonomous robotics, even more so when heavy machinery is involved. Autonomous construction vehicles will never be implemented if there are any doubts about their safeness. Also, having assistance systems improving the safety of a human-driven machine will improve the overall accident rates and is always a good path to pursue.

This work is affiliated with the Robotic Research Lab’s ongoing intention to realize fully autonomous functions on the mobile bucket excavator THOR. The excavator has been equipped with electro-hydraulic control valves, length measurement sensors, and a control PC (among others, see [1]) and is able to perform excavation and loading tasks with only minimum human input. The main sensors for perception are two SICK LMS 151 laser range finders [2], mounted on the cabin (see figure 1). The sensors collect measurement data into a point cloud [3] for ground estimation and object detection. But their primary function is to prevent collisions of the arm during panning movements.

This document shows how laser-based safety scanners can be automatically configured to prevent an autonomous bucket excavator from colliding with humans and objects, and at the same time to allow movements over obstacles like trucks while panning its superstructure.
2 State of the Art

Even with the current degree of automation it is sometimes necessary that a human operator is standing by to supervise a machine, to insert and to remove work-pieces and to initiate the manufacturing process. Often the person is handling material within a danger zone, e.g. between the molds of a hydraulic press. These machines mostly incorporate a light barrier which covers their handling opening so they never move while a worker is replacing a work-piece. This approach works well with machines that have a tightly defined work zone which should not be entered by human workers during normal operation.

With more complex machinery and tasks also the requirements for safety become more complex. As it is not always possible or feasible to fence off a complete area, more sophisticated solutions are needed. Manufacturers of safety equipment have noticed this trend and are providing more powerful sensors to allow for more complex surveillance possibilities.

2.1 Safety Fields

The common way to handle more complex surroundings are the so-called safety fields or safety envelopes. A safety field is defined as a list of minimum and maximum values, one pair for each scan ray. If at least one distance measured is between the corresponding minimum and maximum values, the field is violated and specific countermeasures are taken, e.g. the machine is stopped. An example for field evaluation from [4] is shown in figure 2.

Some range finders only provide a feature called warning fields. These fields are generally similar to safety fields, but usually only notify the user upon field violation without taking any additional actions. Because of this, warning fields are not certified for use in safety-critical applications. But from the conceptual point of view the two types are interchangeable and will be used synonymously in this work.
2.2 Related Work

In [5] a system is presented which utilizes a SICK Laser Measuring Scanner to provide switching warning and safety fields which monitor only the part of an environment in which a robotic arm is currently active, leaving the other part available for persons to stand in (see figure 3a).

The system uses one laser range finder with two safety fields and two warning fields. The safety fields and warning fields are switched in pairs. If the robotic arm is currently active in on the left side, the fields on the right side are active, and vice versa. Having a warning field in front of the entrance to the robot’s cage can be used to give a warning to a worker from accidentally entering the danger zone without interrupting the robot’s work. Setting up this kind of safety is very straightforward. Often range finders provide a teach-in functionality which requires just the press of a button to set up the currently measured situation (e.g. empty robotic cage) as ground truth.

In mobile robotics safety fields are also employed to prevent any accidents (figure 3b), but here the danger zone is moving together with the robot. Automatic teaching of safety fields will not work because the surroundings of the robot are bound to change with its position and orientation. In [6], the safety fields need to be prepared by hand. Depending on the speed and the direction of the vehicle different sizes and shapes of safety fields are activated.
Some laser scanners also offer dynamic fields: simple shapes like rectangles which change their size within predefined limits depending on an external input, i.e. the robot’s speed in encoder ticks.

3 Towards Automatically Configured Safety Fields

As the previous section shows, employing either switching safety fields or dynamic fields can be used to adjust the monitored area according to the currently present state. With a static system like in the first example, setting up the safety fields is very straightforward. It requires just the usage of a teach-in mode where the available space is measured and set as a safety envelope. In the second example, the safety fields are also quite simple, because the movement of the vehicle is limited by its Ackermann-like steering. The possible trajectory can be easily determined in advance and the safety fields can be modelled. Of course, if the position of the safety scanner was changed, the safety fields would have to be recomputed. For simpler envelopes like the ones shown above manual recalculation may be feasible, but for more complex applications (like a bucket excavator) this quickly becomes tedious, especially when working on a research platform and often changing the configuration of the machine (e.g. the sensor position). Figure 4 shows the safety field required in a typical scenario during excavation work.

As dynamic safety fields are restricted to simple geometrical shapes and the excavator’s arm is able to assume rather complicated postures, the approach taken in this work is the switching of pre-defined safety fields. Apart from the calculation of safety envelopes, one of the main problems encountered with this approach is the severely limited amount of safety fields available on a laser scanner. Section 4.2 will address this topic and the chosen solution in detail.
4 Proposed Approach

This section covers the proposed process for automatic safety field generation for any configuration of an articulated robotic arm and any position of the safety scanner. The approach is based on geometrical considerations: When looked at from the side, the sensor and the arm are projected into a plane, making the whole problem two-dimensional. Next, one can easily see that the safety distance for each ray needs to extend beyond all arm segments the ray intersects.

The sensor position $P$ is defined relative to the first arm joint, which is positioned at the origin of the coordinate system. The safety envelopes are generated using ray intersection. Rays are cast from the position of the scanner at a predefined angular resolution. A ray $R_i$ is defined as:

$$ R_i := P + \begin{pmatrix} \cos \beta_i \\ \sin \beta_i \end{pmatrix}. \quad (1) $$

The rays are intersected with each arm segment $S_i$ (introduced in section 4.1, equation 3) using a simple system of linear equations. To ensure full arm coverage, only the intersection point with the greatest distance to the scanner is stored for each scan ray. The design decision was to let the safety fields always begin within the sensor’s center, thus setting the field’s minimum distance to zero. Figure 5 shows the geometrical bare minimum safety envelope for the given arm configuration. In reality, the arm has a thickness which is not taken into account here. It is considered in a later step.
4.1 Preparing a Set of Arm Poses

The generation of safety field descriptions begins with a set of arm poses which are likely to occur during normal operation. These poses are calculated in a nested loop and with distinct ranges and step sizes for each arm joint angle $\alpha_i$. The step size of joints closer to the base needs to be chosen smaller, because of the bigger impact caused by a longer lever arm. The position $J_i$ of each joint can be calculated using forward kinematics:

$$J_i := J_{i-1} + l_i \left( \cos \left( \sum_{k=0}^{i} \alpha_k \right) \right), \quad J_0 := \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

(2)

where $l_i$ is the length of the $i$th arm segment, and $\alpha_k$ are the joint angles. Each pair of joints $J_i, J_{i+1}$ is connected by an arm segment $S_i$:

$$S_i := J_i + t \cdot (J_{i+1} - J_i), \quad t \in [0, 1]$$

(3)

Figure 6 shows an example of several thousand arm poses.

4.2 Arm Pose Clustering

The most important and interesting part is the grouping of the arm poses into a predefined number of clusters. As already mentioned, a safety scanner is only able to store a very small amount of safety field descriptions, in our case 10. To group the generated poses into a given number of groups a clustering technique needs to be employed. Since the number of clusters is known beforehand, the well-known $k$-means clustering [7] has been chosen. This clustering method needs a distance function which is used as measure for intra-group similarity and inter-group dissimilarity.

Finding the right distance metric is the most crucial part of the clustering. The function should yield smoothly varying results when the arm pose is changed by small amounts, it should describe the arm pose in a coherent way, and it should have a small number of parameters (low dimensionality). 
Fig. 6: Example of possible arm poses for a 3-joint-arm (side view). The black dot represents the first arm joint (the arm origin), the red dot is the position of a laser scanner.

One such metric, which has also been found to give very good clustering results, is the Euclidean distance of the geometrical average of each arm pose. It has only 2 dimensions, the geometrical average only shifts slightly when the arm configuration is changed only a little bit, and it has perfectly smooth behavior without any sudden changes.

The geometrical average (or “center of mass”) is easily calculated as

\[ M = \frac{1}{N + 1} \sum_{i=0}^{N} J_i \]  

(4)

where \( J_0 \ldots J_{N-1} \) are joint positions and \( J_N \) is the position of the tool center point. The Euclidean distance of average joint positions (and TCP) fulfills all the requirements listed above for a good metric for arm pose clustering. Figure 7 shows an example of three arm pose groups.

4.3 Safety Fields for Arm Pose Clusters

Having combined the set of all expected arm configurations into 10 clusters of similar configurations, the combination of safety envelopes can be executed. This process involves comparing the individual rays from each safety field and taking the highest value. Additionally, there is a safety distance added to each ray to make up for the simplified arm model which disregards the width of the arm segments. Figure 8 shows the combined safety fields for a few arm configuration clusters.
4.4 Simplifying Safety Fields

Since it is not practical to enter safety fields made from hundreds of points into a laser scanner's configuration interface, the next step is to simplify the safety fields. First the envelopes are smoothed using the local neighborhood. The smoothing algorithm is a bilateral filter where only neighbors with a higher distance to the sensor than the current pivot element are considered. This ensures that the safety distance for all values never drops under their minimum value. Afterwards a recursive line splitting algorithm extracts the most prominent points for the current envelope while substituting the in-between points with line segments. This way most envelopes can be reduced from over 200 points to just 6–10.
5 Conclusion

This document shows a concept for the generation of switchable safety envelopes for a complex robotic arm to prevent collisions during panning movements. The system supports any number of arm joints, arm segment lengths, and any position of the used laser scanner. The computation time takes a few seconds, but has to be done only once per machine configuration.

Right now, the data points for the safety envelopes are printed out for a person to enter into the safety scanner’s configuration interface. Automatically transferring the safety fields to the scanners is not supported by the software, because of legal reasons. The nature of safety fields makes it necessary to have a person in the loop which is responsible for the set-up. This issue should be addressed as one of the next steps.

References