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Safeguarding collaborative mobile manipulators - Evaluation of the VALERI workspace monitoring system

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Abstract

The project VALERI focused on the validation of mobile manipulators for use in aerospace production. This paper focuses on the development and application of a 2 ½ D workspace monitoring system for safeguarding tools when working in close proximity to human operators. Following a brief overview of the set-up and operational principles of the workspace monitoring system, we will detail the assumptions made in the risk assessment and the methods used to minimize the size of the necessary protective distance. An experimental validation and an outlook for future work will also be described in this contribution.

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Keywords: Mobile manipulation; Safe human-robot collaboration; Safety sensors; Risk assessment; Aerospace production; Visual workspace monitoring sensor; Safe collaborative robots; Standardization

1. Introduction

Collaborative robots offer a number of benefits, including being able to physically assist an ageing workforce. However the number of industrial installations featuring collaborative robots is still rather low in comparison to traditional robotics applications. One barrier to more widespread industrial application of collaborative robots is the lack of suitable sensors for safeguarding a robot, its tools, and the workpieces. In the case of mobile manipulators,

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this lack of suitable sensors is even more noticeable. Through their large workspace, mobile manipulators offer a high degree of flexibility and can carry out a number of different tasks at different locations. This increased flexibility unfortunately places further requirements on the safety sensors. In particular, flexible sensor systems able to deal with changing environments and which are able to visually safeguard a mobile robot's manipulator, its tools and any workpieces carried by the robot. A further barrier to more widespread usage of mobile, collaborative robots is uncertainty in the application of the recently released technical specification for collaborative robots, the ISO TS 15066.

The EU-funded project VALERI focused on the validation of mobile manipulators for use in aerospace production, in particular for the tasks of sealant application, sealant inspection, and inspection of braided carbon parts. The Fraunhofer IFF, in addition to project coordination, was responsible for addressing the scientific and technological challenges relating to safety when mobile robots work next to humans without separating fences.

Following a risk assessment of the VALERI robot for the defined applications, we determined there was a need for a variety of safety sensors to safeguard the mobile platform and the tools while carrying out the aforementioned tasks. For the purposes of this paper we will focus on the specific risk of pinching or clamping of human operators while the sealant is being applied by the mobile manipulator. The specific hazard source is the sealant application tool which features a nozzle and is in contact and/or close proximity with the aerospace components. There are currently no commercially-available, safety-rated 3D workspace monitoring systems suitable for use with a mobile manipulator and which are able to detect objects the size of a human finger (≥ diameter 14 mm). Based upon our previous experience with stationary 2 ½D camera systems for workspace monitoring [1], we developed a workspace monitoring system which is mounted above the robot and has pan-tilt capabilities to follow and safeguard the tool. The workspace monitoring system observes the tool, generates and establishes a minimal safety space around the tool, and robustly detects humans or unknown objects that intrude this safety space.

In this paper we will first describe the setup and individual sensor technologies used in the sensor system for providing reliable 2½D sensor data and detecting objects intruding into the virtual safety space around the tool. We will then describe the methods we used to calculate the safety zones, which are based on the industrial application from the VALERI project, the risk assessment, and the safety-distance formulas from the ISO-TS 15066 [2]. In particular we will describe how an initial engineering assessment is carried out, which is extremely conservative and leads to large safety zones. Then we will describe experimental measurements with the robotic system that in our case allowed us to drastically reduce the size of the necessary safety zones around the tool. The experimental results and the implications for future work will be discussed in the final section.

2. Workspace monitoring system for tool safeguarding

The workspace monitoring system was designed to safeguard the tools during sealant application and inspection. The risk assessment showed that there was risk of clamping or pinching between the nozzle of the sealant tool and the part to which sealant is being applied, as well as risk of impact when the inspection tools were being used. We chose to develop a workspace monitoring system which can follow the different tools and safeguard them while in operation. The workspace monitoring system developed consists of a stereo camera system combined with a time-of-flight (ToF) camera, so that they can each compensate for individual disadvantages of the other one. The stereo camera system uses three grayscale cameras that form three redundant stereo pairs, to increase the robustness of the matching and ultimately offer a high reliability of 2 ½ D sensor data on feature-intensive (structured) areas. The ToF camera complements the stereo data for reliable 2 ½ D sensor data for homogeneous (unstructured) areas). The design of the system is shown in Figure 1. A detailed description of the operating principles and sensor fusion can be found in [3].

Fig. 1. Workspace Monitoring System with three stereo cameras and one time-of-flight camera. (a) Schematic design; (b) Actual sensor system.

The sensor system is mounted on a pan-tilt unit so that the camera field of view can follow of the tool. This entire module is mounted on top of the linear axis of the mobile platform. The main surveillance area begins at a distance of 500 mm from the cameras and reaches up to 2000 mm.

3. Determining the size of the safety zones

In the following section, we will describe two methods to determine the size of the safety zones for the optical workspace monitoring system when safeguarding the sealant application tool by means of Speed and Separation Monitoring. While some may consider this step to be trivial given that the ISO-TS 15066 offers an equation for determining this, we would like to demonstrate through a concrete example how complicated this can nevertheless be for system integrators in practice. Furthermore, we would like to mention briefly some of the assumptions and design decisions we made so that the size of the safety zones can be kept to a reasonable minimum. These decisions can influence the feasibility of a collaborative robotic application.

3.1. General considerations

The ISO-TS 15066 is the most relevant standard for determining the size of safety zones during the safeguarding mode Speed and Separation Monitoring. The general equation for determining the protective separation distance, S_p, is given by the equation (1):

$$S_p = S_h + S_r + S_s + C + Z_d + Z_r \quad (1)$$

whereby S_h is the contribution dependent on the operator's change in location, S_r is the contribution based on the robot's reaction time, S_s is the contribution based on the robot's stopping distance, C is the intrusion distance, as defined in the ISO 13855 [4], which is how far a body part can intrude into the sensing field before it is detected, Z_d is the measuring tolerance (position uncertainty of the person in the collaborative workspace) and Z_r is the position uncertainty of the robot which results from the accuracy of the robot's position measurment system.

A simplified equation to determine S_h and S_r can be seen in equations (2) and (3), respectively:

$$S_h = v_h \times (T_r + T_s) \quad (2)$$

$$S_r = v_r \times T_r \quad (3)$$

In these simplified cases, which assume a constant speed for an approaching human, v_h, and a constant robot speed v_r, we also need the reaction time of the robot system, T_r, which includes the time required for the detection of operator position, signal processing, activation of stop command, but excluding the braking time, and the stopping time of the robot, T_s, which includes the time from the activation of a stop command until the robot has halted its motion. Of course, the values for T_s are not constant and can vary greatly depending on the robot payload, configuration, and speed.

As a first assumption we extrapolated values for T_s and S_s from the manufacturer data sheets [5]. We assumed 66% arm extension and 100% payload[1]. While the joint speeds are all well under 33% of the maximum joint speed, we nevertheless used this as a worst-case value, given that there is no further information in the manufacturer data sheets with which we could extrapolate a meaningful value. It should be noted that the manufacturer data sheets specify the stopping distance and time for an individual joint. Since the tool is applying sealant in a straight line, the movement of the robot is a combination of multiple joints. An extremely conservative estimate could involve summing the stopping distance for all joints.

According to ISO 13855, a nominal approaching speed of a human can be assumed to be 1.6 m/s. Table 1 shows the first assumptions for the values of the individual components and the ensuing size of the safety zone around the tool. Granted this is a quick and conservative assessment, the required minimum distance between an approaching human and the tool, which is only moving at 35 mm/s, is over 1.5 m! The end-users in the VALERI consortium, both Airbus Defense and Space and FACC, stated in their initial requirements that the robot should perform as continuously as possible without interruptions due to passing persons. Indeed, in order to make economic sense and to ensure a high quality sealant bead, it was considered of upmost importance that humans be allowed to get up to touching distance before having the robot stopped. The reality on the factory floor is that operators are continuously working on different areas of the same part that the robot is working on, and closing off such a large area around the VALERI robot would have make it unviable in practice.

Table 1. First assumptions for solving Equations 1-3 to determine size of safety zone

Parameter	Value	Comments
v_h	1600 mm/s	Standard assumption when it is not possible to measure the speed of approaching humans
v_r	35 mm/s	Max. tool speed (limited by sealant application process)
T_r	0.25 s	First assumption. To be measured or verified later.
T_s	0.60 s	From manufacturer data sheet
S_h	1360 mm	Contribution to safety zone due to approaching human
S_r	8.75 mm	Contribution to safety zone due to robot speed
S_s	213 mm	Extrapolated from manufacturer data sheet assuming only axis 1 movement, 66% arm extension, 100% payload and 33% of max. speed
C	0 mm	Assuming a detecting ability of 14 mm
Z_d	5 mm	Measurement uncertainty from sensor system
Z_r	1 mm	Positioning uncertainty of robot
S_p	**1588 mm**	**Necessary protective distance for Speed and Separation Monitoring**

3.2. Application-specific considerations

In this section we will describe the assumptions and considerations undertook in the VALERI project that are application-specific in order to reduce the size of the required safety zone so that the overall feasibility of the application could be achieved. Reviewing the values in Table 1, we see that over 80% of the size of the safety zone is due to the term S_h, which itself is dependent on assumptions for the approaching speed of the human, v_h, and conservative extrapolated data regarding T_s. Therefore a useful first step is to determine whether these values can be determined more accurately than by initial assumptions.

[1] The sealant application tool and tool changer together weigh approximately 6,9 kg.

If a robotic system is unable to measure the approaching speed of a human, a useful analogy is to imagine that the robot is blindfolded and therefore assumes people are moving towards it with a speed of 1600 mm/s all the time. If however, we are able to measure the speed of incoming objects such as humans with the optical workspace monitoring system, then we can use real measured values to dynamically determine the size of the necessary safety zone. People who are working in the vicinity of the VALERI robot can continue working and the robot will not stop until a truly dangerous situation occurs. Therefore a first step is to also use the workspace monitoring system to determine the speed of incoming objects.

A second step is to more accurately determine the time, T_s, experimentally. We know that the value we used in Table 1 is a conservative estimate. Nevertheless, without proper verification, it is invalid to arbitrarily choose another one. The methods used here will be described in Section 4.

Further application-specific assumptions are as follows:

- Intended use of the sealant tool and the VALERI system does not require human operators to come in contact with the sealant tool during this process. This can be classified as *parallel cooperation* [6].
- Foreseeable misuse includes the case whereby an operator who is working in an area into which VALERI is moving quickly moves their hands/arms to grab a part or component (e.g. screw, tool) which close to the sealant tool.
- Only the sealant tool is being safeguarded by the workspace monitoring system during the operational phase “sealant application”.
- The mobile platform is safeguarded during sealant application by power and force limiting.
- The arm itself is also safeguarded by power and force limiting. Were the arm to also be safeguarded by the workspace monitoring system, the required workspace would be much larger and would also require a complete 3D analysis of the entire kinematic chain of the robotic arm to find local speeds as described in [7].
- The parts upon which the VALERI robot performs work are long and the area where sealant is being applied is not accessible to humans from the back side. Therefore it can be understood that humans can only approach from the left and right side (e.g. in the direction of motion or from behind).

4. Experimental evaluation of workspace monitoring system

In the following section we will describe the measurements we carried out to determine the value of S_r, T_r, and T_s.

4.1. Measurement of robot stopping distance of robot, reaction time, and stopping time

In order to get more accurate values for the stopping distance of the robot, the reaction time of the robotic system including the processing time for the safety sensor, and the stopping time of the robot, we used a linear travel measuring system with a draw wire from *hhb electronic*. Figure 3 shows the set-up. In this set-up, a moveable flag is triggered and enters the robot’s safety zone during sealant application. This is recognized by the workspace monitoring system and a stop command is sent to the robot arm. The time between when the flag is triggered and the robot stops is measured, as well as the overall distance traveled is measured. This system has the advantage of not needing to be connected electronically with the robot control system, but it did require a mechanical connection for the draw wire to the tool of the robot. The measurements took approximately 2 hours to complete.

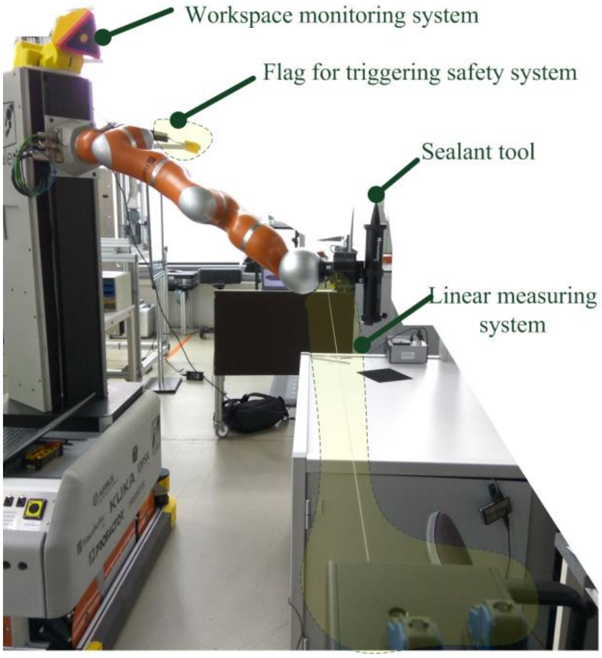

Fig. 3. Measurement set-up to determine the robot's stopping distance, reaction time, and stopping time.

4.2. Experimental results

The results from the measurements are listed in Table 2. In particular we measured a much shorter time between when the safety zone is violated and the robot stops ($T_{r+} T_s$), as well as a much shorter robot stopping distance, S_s.

Table 2. Determining necessary protective distance with measured values

Parameter	Value	Comments
v_h	1600 mm/s	Worst-case speed of human operator
v_r	35 mm/s	Max. tool speed (limited by sealant application process)
$T_{r+} T_s$	0.35 s	Measured reaction and stopping time
S_h	560 mm	Contribution to safety zone due to approaching human
S_r	8.75 mm	Contribution to safety zone due to robot speed
S_s	10 mm	Measured stopping distance of robot
C	0 mm	Assuming a detecting ability of 14 mm
Z_d	5 mm	Measurement uncertainty from sensor system
Z_r	1 mm	Positioning uncertainty of robot
S_p	585 mm	Necessary protective distance for Speed and Separation Monitoring

With these measured values, we see that the minimal protective distance given a worst-case whereby a human approaches the robot speed of 1600 mm/s is now only 585 mm. Furthermore, if the approaching speed of a nearby operator is measured by the workspace monitoring system and found to be less than 1600 mm/s, the distance at which the robot must stop can be even smaller. As an example, Figure 4 illustrates a case where an operator is working next to the robot and reaches with their hand close to the sealant tool to grab a part (e.g. a rivet or a screw). In a situation with a hand speed of 500 mm/s, the system would not need to stop until the human is within 200 mm of the tool. The system of course needs to be able to detect objects at the largest necessary protective distance determined in Table 2, but as long as approaching speeds are lower than 1600 mm/s, smaller safety distances are possible and a human can get closer without requiring the robot to stop.

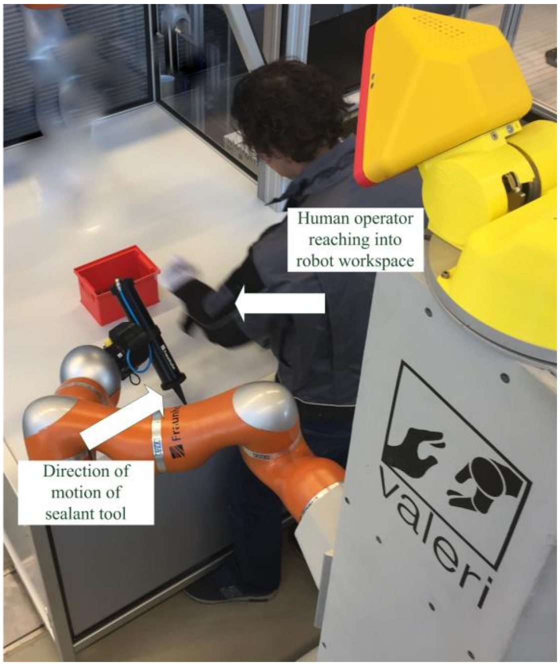

Fig. 4. Situation whereby a human operator works next to VALERI and reaches into safety zone

We would furthermore like to note the important role of the high resolution of the workspace monitoring system in determining the size of the safety zone. In our calculations, the resolution of the sensor was calculated as 14 mm (for determining the intrusion distance, C). This corresponds to being able to determine whether a human finger has entered the safety zone. Other commercially available workspace monitoring systems have a resolution in the range of 40 mm, meaning that an arm is the smallest body part which can be reliably detected. With such standard components, the worst-case necessary protective distance for our case would have increased from 1588 mm up to 1796 mm, and in our improved scenario, from 585 mm up to 793 mm.

5. Conclusion

We presented a workspace monitoring system for safeguarding a tool of the mobile manipulator, VALERI, during the process of applying sealant to large aerospace parts. In addition to briefly describing the sensor system itself, we discussed the method that can be used to determine the size of the protective separation distance between the tool and a human operator. We showed how a quick engineering analysis could lead to extremely conservative values which would immediately put the feasibility of the application in question. We then demonstrated which assumptions can be made based on the particular application and which measurements can be carried out to minimize the size of the protective distance to an absolute minimum. In this case, a reduction in the required size of the safety zone from 1588 mm to 585 mm (and even less, depending on the operator’s approaching speed) could be accomplished. Furthermore we showed how the high resolution of the workspace monitoring system (it is able to detect objects with a diameter of 14 mm) is an important factor in achieving such small necessary protective distances.

While the first version of the technical specification ISO-TS 15066 has recently been published, we believe that there are still quite a few unanswered questions regarding how best to apply the standard. Collaborative robotics applications are of high complexity due to the interaction between the various components including the robot, the tool, the workpieces, the human, the safety sensors, the application, the environment, etc. Currently there are no design and modeling tools available which can effectively take all of these factors into account and support engineers during the design phase. In particular it would be very useful for the robotic application designer to be able to easily see and understand the tradeoffs between the different parameters to arrive at optimal solutions more quickly. As we have shown, the system needed to be built up and evaluated experimentally before reaching a better solution. This however requires a leap of faith by system integrators and end-users, is a cost driver, and a barrier to more widespread use.

Given the current situation, there is strong need for future work in determining best practice for applying the standard, especially to make design decisions more understandable for system integrators and the end-users. We also see that the workspace monitoring system, through its ability to detect the speed of approaching humans with a high resolution, is a good approach and is currently being further developed in the H2020 project ColRobot. It allows for safety zones to be much smaller than would otherwise be the case, saving up floor space on the shop floor and making more applications feasible that otherwise would not be.

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