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The influence of collision avoidance strategies on human-robot collaborative systems

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Abstract: Collaborative robots improve the traditional production systems, both automatic and manual, by allowing the resources to share the workspace. However, the shared workspace is both the greatest advantage and limit of collaborative robots. Indeed, interference between the human operator and the cobot may result in an emergency stop, reducing the performance of the system. Hence, a collision avoidance strategy is required to avoid collision; however, this may affect the performance of the system. Therefore, it is necessary to investigate how the shared workspace affects the system performance, and the effects of the adoption of a collision avoidance strategy. To this regard, a collision avoidance strategy has been developed and it is presented in this work and an experimental validation proved the efficacy of the proposed strategy. Lastly, simulation tests were carried out to analyse the performance of the system for different sizes of the collaboration area with respect to the workspace. The results shows that, while the increase in the collaboration area reduces the performance of the system, collision avoidance strategies mitigate this effect.

Keywords: Collision avoidance, collaborative robotics, human-robot collaboration, shared workspace

1. INTRODUCTION

The recent trend in the market requires for customized mass production, i.e., providing the customer for a wide range of different products without increasing the cost or lead time (Tseng et al. (1996)). In recent years, collaborative robots, or simply cobots (Colgate et al. (1996)), have been adopted to improve the flexibility of production systems. Indeed, the main feature of these manipulators is the ability to share their workspace with the human operator without the need for safety fences. Hence, it is possible to merge the flexibility and dexterity of human operators with the repeatability of the robotics manipulator, thus avoiding the issues of manual systems, i.e., ergonomics and human errors.

However, the presence of the human operator leads to safety issues, which are further aggravated by the unpredictable nature of the human motions. Hence, it is fundamental to detect the operator position in the collaborative workcell, to identify possible collisions in real time. Moreover, for a collaborative system to be effective, it should actively avoid any collision to avoid stops that would reduce its productivity. Therefore, it is necessary to monitor the human operator and replanning the robot trajectory accordingly.

Recently, the recognition of the human operator pose has been carried out through the use of Motion Capture (MOCAP) technology, as seen in Bortolini et al. (2020). Marker-based optical MOCAP is based on active or passive markers properly displaced on specific parts of the operator body. Alternatively, inertial measurement units (IMU) (Bourke et al. (2008)) could be adopted to perform Inertial MOCAP techniques. However, both approaches are nor suitable for real-world applications on collaborative workcells, due to the need for specific hardware, such as suits. The suits may be cumbersome and interfere with the worker activity; moreover, they only capture the wearer's motion, whereas the surrounding of the wearer is not considered.

On the other hand, markerless optical MOCAP, i.e., vision based methods such as 3D surveillance (Krüger et al. (2005)), is performed with a proper computer vision algorithm, which analyze and process the images recorded by cameras to recognize the human operator from the background static scene during his/her activies (Lv et al. (2018)). Regarding the accuracy, the development of depth camera systems ensures a good measurement accuracy and built-in algorithms for operator recognition (Lien et al. (2006)).

In Mohammed et al. (2017) the operator is identified as a point cloud from the depth images from two Kinect sensors. The point cloud is then used to generate an augmented environment alongside the 3D model of the robot, allowing the system to effectively calculate the distance

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between the resources. In Du et al. (2018) a single Kinect is employed to detect the human operator, using the integrated libraries to derive 15 skeleton joints. Since the position is ill-defined when occlusions are encountered, and a unscented Kalman filter, which is based on unscented transformation to estimate the signals,is adopted to reduce the influence and uncertainty of time varying signals. In Safeea and Neto (2019) human tracking is carried out from both marker-based vision systems and IMU sensors. By merging both sensors it is possible to obtain accurate measurements without the drawbacks of both systems, i.e., small areas of analysis and drift, respectively. Moreover, the IMUs are used for upper body tracking, while the position of the legs is acquired from laser scanners installed at the base of the robot working table. This setup is motivated by the need to have accuracy in centimetres scale for the upper body, since the arms can be very close to the robot while the torso is relatively far.

As stated before, an active collision avoidance approach needs to adapt the robot trajectory to the operator presence to avoid collision. Ferraguti et al. (2020) presents a collision avoidance approach based on Control Barrier Functions, i.e., functions that constraints the system state inside a safe set. In the proposed work, the adopted function is based on the joints acceleration, and a quadratic optimization problem plans the trajectory by minimizing the difference between the commanded and desired joint acceleration, while respecting the constraints given by the safety barrier function. An artificial potential fields approach is adopted in Scimmi et al. (2021). This approach imposes repulsive and attractive velocities to the end-effector velocity, where repulsive velocities are associated to the operator and attractive ones to the desired task position. Changing the robot velocity modify the planned trajectory and effectively moves the robot away from the operator. Lastly, in Scoccia et al. (2021) a collision avoidance strategy for redundant manipulators is presented. Indeed, the additional joint allows the robot to reach a position with different configurations, which is fundamental for collision avoidance applications. Starting from artifical potential strategies, the authors proposed a method that governs the redundancy of the manipulator and changes the trajectory of the end-effector in real-time.

While the importance of collision avoidance strategies is undeniable due to safety issues, their influence on the system performance have not been investigated, especially in terms of collaboration between the resources. Indeed, as the collaboration area is expanded through the workspace, the risk for interference between the resources increases, Therefore, it is necessary to investigate the effect of the collaboration area on the performance of a collaborative system and how a collision avoidance strategy affects their relation.

In this work, a collision avoidance strategy is presented and tested in an experimental setup. The approach is based on geometric conditions that allows to maintain the robot speed while changing its direction of motion to avoid collision. Indeed, by moving along the tangent lines between the bounding volumes it is possible to obtain the shortest path while avoiding obstacles (Ibrahim et al. (2016)). This work aims to:

- provide for a fast collision avoidance strategy suitable for real time applications;
- investigate the influence of the collaboration area on the performance of the systems, i.e., the collaboration between the resources and the productivity;
- investigate the effects of passive and active collision avoidance strategy on the influence of the collaboration area.

This work is structured as follows: section 2 presents the proposed collision avoidance strategy; section 3 presents the experimental validation of the proposed approach and discusses the influence of the collaboration area on the performance of the system. Lastly, section 4 concludes the work.

2. COLLISION AVOIDANCE STRATEGY

2.1 Resources modeling

Similarly to previous works, the resources are modeled as capsules, or sphere-swept volumes, i.e., the volume swept by a sphere alongside a direction. Hence, all points of the surface of the SSV are equidistant from the inner medial structure, in this case a line. This description allows for several advantages (Bae et al. (2012)):

- tight fit;
- efficient distance computation;
- simple intersection tests

which make it suitable for our application. To define the capsules surroundings the operator and the robot links, it is necessary to define:

- nodes, i.e., the end-points of the line,
- radius of the basic sphere, i.e., the distance of each point of the surface from the medial structure.

While an appropriate radius for the robot links can be estimated from the datasheet or the CAD data of the robot, their nodes are obtained from direct kinematics given the robot joint position. On the other hand, a skeletonization technique is required to obtain the node position, i.e., key-points, of the operator. Moreover, traditional techniques does not provide for a radius for the SSV; hence, our method, which will be presented later, need to provide an evaluation of the radius. Lastly, the proposed description allows easily evaluating possible collision between the resources by evaluating the minimum distance between their inner medial structures. To evaluate the distance between two line segments, the approach presented in Ericson (2004) is adopted in this work.

2.2 Active collision avoidance approach

Given the distance between the resources in each frame, it is possible to identify possible collision and if it is required to modify the trajectory. The proposed approach adopts the following hypothesis:

- since this approach is applied to fast application with high frequency of sampling, it is possible to approximate the operator as a static obstacle with different position in each frame;
- the robot end-effector moves along a cartesian linear trajectory;

- the SSVs are modeled as 2D objects.

The evaluation of the collision avoidance trajectory is carried out in two phases:

- evaluation if the destination for each timestep is reachable and does not lead to collision;
- evaluation of possible collision during the motion towards the destination for each timestep.

This distinction is fundamental, since the adopted method to avoid collision during the motion is not solvable if the destination is not reachable.

If the algorithm detects a possible collision in the robot destination, it evaluates and define a new safe destination, which aims to move the robot towards the goal while keeping a safe distance with the operator. To keep a safe distance between the resources, our approach aims to move the end-effector along the tangents of the SSVs. This evaluation depends on the position of the closest points on the line segments and 3 cases can be identified:

- both closest points are the line segments end-points;
- the closest point of the robot link segment lays inside the segment, while the closest point of the operator link segment is an end-point
- the closest point of the operator link segment lays inside the segment, independent of the position of the robot closest point.

Each scenario requires a different approach due to the different conditions that it imposes; moreover, applying the appropriate method allows to reduce the computation time.

End-points as closest points In this scenario, represented in Figure 1, the closest points are the line-segments end-points; hence, the contact area between the resources is the intersection between two circles.

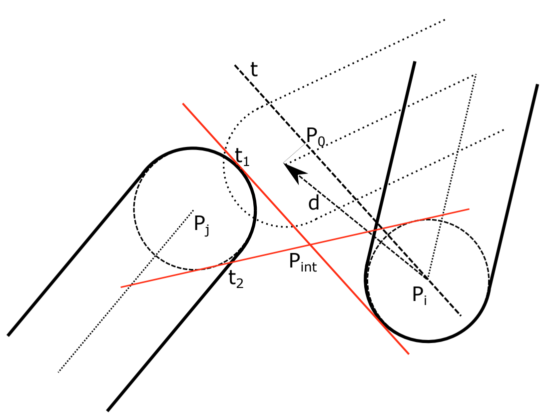

Fig. 1. Example of collision on the end points. The red lines are the tangent lines on the robot end-effector P_i and operator hand P_j. P_0 represent the modified destination to avoid collision.

The optimal direction of motion is evaluated considering the inner tangent lines between the SSVs closest endpoints. Indeed, the end-effector should move along the tangent with the operator end-point to avoid collision. Thus, the inner tangent lines are evaluated by first calculating the intersection point P_{int}

$$\mathbf{P_{int}}^T = [r_i r_j] \left[\mathbf{P_j P_i}\right]^T / (r_i + r_j) \qquad (1)$$

where $\mathbf{P_i}$ and $\mathbf{P_j}$ are the position of the robot end-effector and human operator hand, respectively. From this, the coordinates of the tangent points on the circumference i are evaluted as:

$$t_{x_{1,2}} = \frac{r_i^2(P_{int_x} - P_{i_x}) \pm r_i(P_{int_y} - P_{i_y})rt}{den} + P_{i_x} \qquad (2)$$

$$t_{y_{1,2}} = \frac{r_i^2(P_{int_y} - P_{i_y}) \mp r_i(P_{int_y} - P_{i_y})rt}{den} + P_{i_y} \qquad (3)$$

where P_{int_x} and P_{int_y} are the x and y components of $\mathbf{P_{int}}$; similarly for P_{i_x} and P_{i_y}). rt and den are calculated as:

$$rt = \sqrt{(\mathbf{P_{int}} - \mathbf{P_i}) \cdot (\mathbf{P_{int}} - \mathbf{P_i}) - r_i^2} \qquad (4)$$

$$den = (\mathbf{P_{int}} - \mathbf{P_i}) \cdot (\mathbf{P_{int}} - \mathbf{P_i}) \qquad (5)$$

However, two points t_1 and t_2 are evaluated in this way. To avoid further collisions, the robot end-effector should move farther to the operator SSV; hence, the algorithm chooses the tangent point farther to the inner medial line of the operator SSV, which is t_1 in Figure 1. To ensure the collision avoidance, the direction of motion should follow the chosen tangent direction t. Hence, the destination of the end-effector P_0 is evaluated as the projection of the direction of motion d on t.

Robot link closest point inside the segment In this scenario, closest point of the robot link segment lays inside the segment line,as seen in Figure 2.

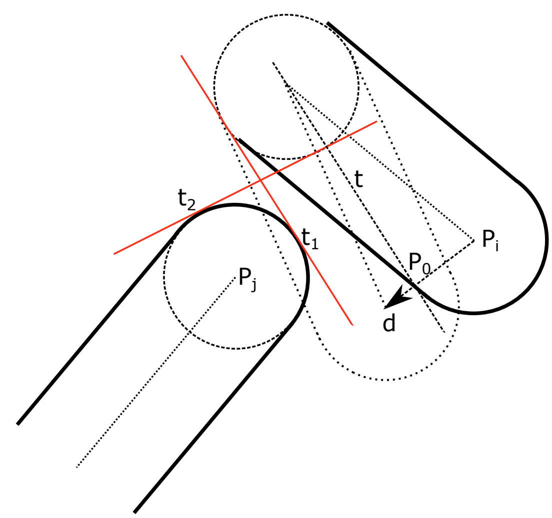

Fig. 2. Example of collision on the robot inner structure. The red lines are the tangent lines on the robot base and operator hand P_j. P_0 represent the modified destination to avoid collision.

Similarly to the previous discussion, the end-effector of the robot should move along the tangent lines of both the operator end-point and the robot base end-point. Indeed, the end-effector should move along the tangents to operator end-point to avoid collision. However, considering the SSV on the end-effector for the tangent method still leads to collision inside the SSV. A solution is to consider the robot base; indeed, the side of the SSV is tangent to the robot base circle by definition. Hence, inner tangent lines between the operator end-point and the robot base end-point are suitable to satisfy both this condition and are evaluated as seen in 2.2.1. Between the two tangent points t_1 and t_2 obtained, the algorithm chooses the nearest one to the robot current position, otherwise the SSVs would intersect. Hence, the direction t that the end-effector should adopt to avoid collision is defined as the parallel to the tangent line with a distance equal to the robot radius. To ensure that the end-effector moves towards the goal, the robot destination P_0 is set as the intersection between the safety direction t and the nominal trajectory d.

Operator link closest point inside the segment Differently from the previous scenarios, the tangent line to the operator SSV cannot be evaluated as the tangent line to a circle, since they do not ensure to avoid collision with the operator arm. Hence, the tangent line considered in this scenario is inner medial structure of the SSV, as seen in Figure 3.

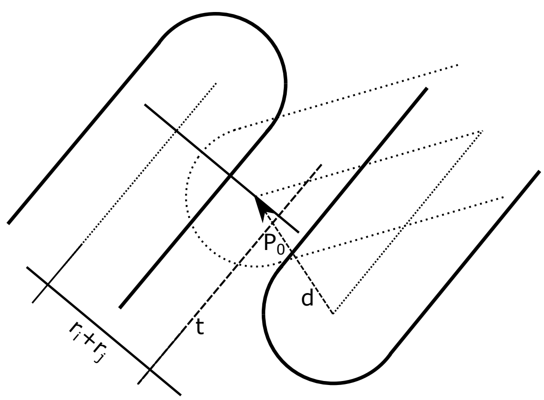

Fig. 3. Example of collision on operator inner structure. The dashed line t is the tangent line that avoid collision between the resources. P_0 represent the modified destination to avoid collision.

Hence, the direction that the robot should adopt to avoid collision t is defined as the line parallel to the the inner medial structure and with a distance equal to the sum of the resources' radii r_i and r_j. Again, to ensure that the end-effector moves towards the goal, the intersection between t and the nominal trajectory d is adopted as the robot destination P_0.

2.3 Collision avoidance along the path

Subsequently, it is necessary to evaluate a collision avoidance approach along the trajectory. To evaluate if a collision is possible along the robot motion, the distance between the robot trajectory and the operator position is evaluated as in 2.1. The proposed approach consider 2 sets of inner tangent lines:

- tangent lines between the current position of the end-effector and the operator end-point;
- tangent lines between the destination of the end-effector and the operator end-point.

In both cases the tangent line further to the opposite operator end-point is considered. The intersection between both tangent lines is the viapoint of the robot end-effector which ensure to move the end-effector while avoiding possible collisions.

3. RESULTS AND DISCUSSION

3.1 Experimental setup

Experimental tests are necessary to assess the validity of the proposed strategy since some effects could not be considered in the simulation algorithm. For this purpose, a prototype collaborative workcell has been developed in the Robotics and Automation Laboratory at the Department of Management and Engineering of the University of Padova. The adopted collaborative robot is a KUKA LBR iiwa 14 R820, a cobot widely used by the industries.

To monitor the operator position, a Intel Realsense D435 depth camera has been adopted, and the depth image has been used to identify the operator from the environment. A laptop with a AMD Ryzen 7 4800H CPU was used to perform the analysis, and the operator identification and collision avoidance strategy required 0.05 s each, which is compatible with real-time requests. As seen in Figure 4, the robot trajectory in cyan shows that the robot successfully avoids the operator and moves to the requested target task.

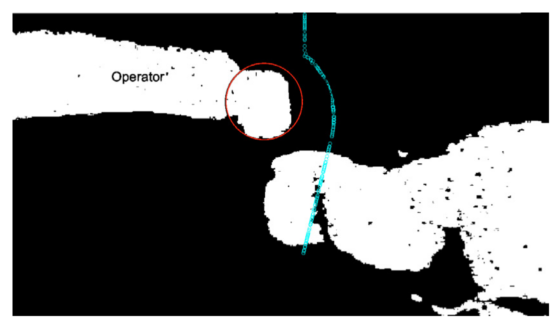

Fig. 4. Experimental tests: in red the operator SSV around the hand and in cyan the robot trajectory.

3.2 Discussion

The simulation environment presented in Boschetti et al. (2021) was adopted to identify the influence of the collaboration area on the makespan T and the collaboration between the resources, as well as the effects of the adoption of a collision avoidance strategy. The collaboration was modeled as in Faccio et al. (2020), where it is defined from the shared time between the resources T_{coll}

$$T_{coll} = t_{a,m} + t_{a,r} - T_{tot,a} \tag{6}$$

where $t_{a,m}$ and $t_{a,r}$ are the assembly time of the operator and the robot, respectively, and $T_{tot,a}$ is the total assembly time. From these, the collaboration parameter $c_{\%}$ is defined as:

$$c_{\%} = \frac{T_{coll}}{T_{tot,a}} \tag{7}$$

On the other hand, we considered the makespan as a measure of the productivity as we considered the assembly of a limited number of products, as in Faccio et al. (2020).

The collaboration area is defined in terms of the ratio A_r between the total area and the shared workspace. Considering a uniform density of tasks in the workspace, it is possible to evaluate A_r as:

$$A_r = \frac{N_{ts}}{N_p} \tag{8}$$

where N_{ts} is the number of tasks in the shared workspace and N_p the total number of tasks. Six differen values for A_r were considered: 0, 20%, 40%, 60%, 80% and 100%. This allowed to consider different collaboration scenarios from the coexistence methodology to different degrees of cooperation(Müller et al. (2016)). To avoid considering effects on the collaboration due the product characteristics such as product size and number of tasks, the product side length and number of tasks considered were fixed at 600 mm and 20 tasks, respectively. The product size was defined accordingly to the size of the two SSVs in order to avoid collision due to the restricted workspace size rather than to the collaboration area. Different number of tasks and greater product size were also considered, showing similar results. Moreover, to avoid considering the influence of the task allocation on the collaboration, 8 different task allocations were considered for each A_r, assigning to each resource the proper tasks to obtain the desired value of A_r, leading to a total of 48 simulations.

Other process characteristics (Boschetti et al. (2021)) considered were the resources assembly times t_a and picking times t_{pp} and whose values, along with the SSVs data, are taken from Boschetti et al. (2021) as seen in Table 1.

Table 1. Values of the input variables and parameters

Manual parameter	**Value**	**Unit**
t_a	$1.04 \cdot 10^{-3}$	h/part
t_{pp}	$3 \cdot 10^{-4}$	h/part
s	$7.2 \cdot 10^5$	mm/h
L_{min}	0	mm
L_{max}	600	mm
R	95	mm
Robot parameter	**Value**	**Unit**
t_a	$2.1 \cdot 10^{-3}$	h/part
t_{pp}	$1.94 \cdot 10^{-4}$	h/part
s	$9 \cdot 10^5$	mm/h
L_{min}	65	mm
L_{max}	1300	mm
R	90	mm

As a first result, Figure 5 proves that the extent of the collaboration area in regards to the workspace influences the risk of collision, therefore, increasing the need for a collision avoidance strategy. The Figure shows the mean number rounded to lowest value of collision avoidance strategy usages for different A_r in blue, with the red errorbars indicating the maximum variation from the mean.

As the collaboration area increases, the possibility of interference between the resources increases, thus decreasing $c_{\%}$, as seen in Figure 6.

Indeed, as per the definition of $c_{\%}$, a passive collision avoidance strategy, i.e., stopping the robot in case of collision, will further reduce T_{coll}, hence, reducing the collaboration, as identified by the red line. Adopting a collision avoidance strategy, while increasing the motion time and therefore reducing $c_{\%}$ in comparison to a linear trajectory, allows to mitigate the effects. This is showed by the blue line in Figure 6, obtained with a linear regression.

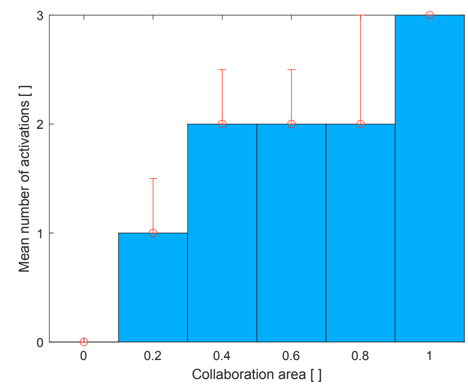

Fig. 5. Mean number of collision avoidance strategy uses for different collaboration areas, in red the maximum error.

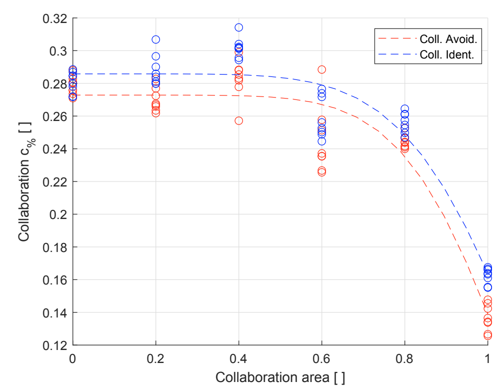

Fig. 6. Effect of the collaboration area A_r on the collaboration parameter $c_{\%}$. The red data are obtained using a passive collision avoidance strategy, the blue ones using the proposed collision avoidance strategy.

As seen in previous works (Faccio et al. (2020); Boschetti et al. (2021); Faccio et al. (2019)), an increase in $c_{\%}$ leads to a reduction of the makespan T, and similar results can be seen in Figure 7.

Indeed, reducing $c_{\%}$ corresponds in both scenarios to an increase of the makespan. However, the increase is mitigated by the collision avoidance strategy. Lastly, the diverging behaviour is motivated by the increasing number of collission avoidance strategy usages due to the higher value of A_r.

4. CONCLUSIONS

This paper presents a collision avoidance strategy for human-robot collaboration, which is based on the definition of tangents to the SSVs of the resources. The proposed approach is adopted to identify the influence of the collaboration area on the interference between the resources and on the makespan. This work leads to the following results:

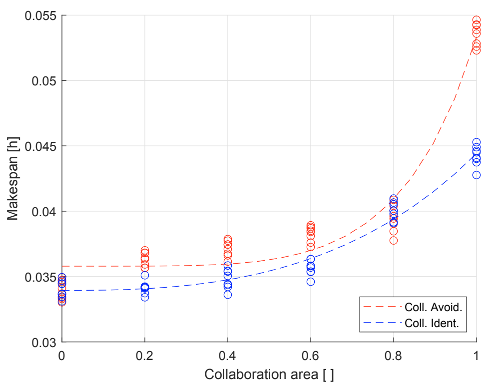

Fig. 7. Effect of the collaboration area A_r on the collaboration parameter $c_{\%}$. The red data are obtained using a passive collision avoidance strategy, the blue ones using the proposed collision avoidance strategy.

- increasing the collaboration area leads to an increase of the interference between the resources, reducing $c_{\%}$;
- adopting an active collision avoidance strategy allows to reduce the idle time and mitigate the reduction of $c_{\%}$
- the influence of $c_{\%}$ on the makespan is confirmed, showing an increase of T due to the reduction of $c_{\%}$.

Future works will further investigate the relation between the collaboration area and $c_{\%}$, in order to extend the collaboration parameter to consider both the shared times and the workspace.

REFERENCES

Bae, M., Kim, J., and Kim, Y.J. (2012). User-guided volumetric approximation using swept sphere volumes for physically based animation. *Computer Animation and Virtual Worlds*, 23(3-4), 385–394. doi: https://doi.org/10.1002/cav.1461.

Bortolini, M., Faccio, M., Gamberi, M., and Pilati, F. (2020). Motion analysis system (mas) for production and ergonomics assessment in the manufacturing processes. *Computers & Industrial Engineering*, 139, 105485. doi:https://doi.org/10.1016/j.cie.2018.10.046.

Boschetti, G., Bottin, M., Faccio, M., and Minto, R. (2021). Multi-robot multi-operator collaborative assembly systems: A performance evaluation model. *Journal of Intelligent Manufacturing*, 32(5), 1455–1470.

Bourke, A., O'Donovan, K., and ÓLaighin, G. (2008). The identification of vertical velocity profiles using an inertial sensor to investigate pre-impact detection of falls. *Medical Engineering & Physics*, 30(7), 937–946. doi:https://doi.org/10.1016/j.medengphy.2007.12.003.

Colgate, J.E., Edward, J., Peshkin, M.A., and Wannasuphoprasit, W. (1996). Cobots: Robots for collaboration with human operators.

Du, G., Long, S., Li, F., and Huang, X. (2018). Active collision avoidance for human-robot interaction with ukf, expert system, and artificial potential field method. *Frontiers in Robotics and AI*, 5, 125. doi: 10.3389/frobt.2018.00125.

Ericson, C. (2004). *Real-time collision detection*. Crc Press.

Faccio, M., Bottin, M., and Rosati, G. (2019). Collaborative and traditional robotic assembly: a comparison model. *The International Journal of Advanced Manufacturing Technology*, 102(5), 1355–1372.

Faccio, M., Minto, R., Rosati, G., and Bottin, M. (2020). The influence of the product characteristics on human-robot collaboration: a model for the performance of collaborative robotic assembly. *The International Journal of Advanced Manufacturing Technology*, 106(5), 2317–2331.

Ferraguti, F., Talignani Landi, C., Costi, S., Bonfè, M., Farsoni, S., Secchi, C., and Fantuzzi, C. (2020). Safety barrier functions and multi-camera tracking for human–robot shared environment. *Robotics and Autonomous Systems*, 124, 103388. doi: https://doi.org/10.1016/j.robot.2019.103388.

Ibrahim, Z.Y., Rashid, A.T., and Marhoon, A.F. (2016). An algorithm for path planning with polygon obstacles avoidance based on the virtual circle tangents. *Iraq J. Electrical and Electronic Engineering*, 12(2), 221–234.

Krüger, J., Nickolay, B., Heyer, P., and Seliger, G. (2005). Image based 3d surveillance for flexible man-robot-cooperation. *CIRP Annals*, 54(1), 19–22. doi: https://doi.org/10.1016/S0007-8506(07)60040-7.

Lien, J.M., Keyser, J., and Amato, N.M. (2006). Simultaneous shape decomposition and skeletonization. In *Proceedings of the 2006 ACM Symposium on Solid and Physical Modeling*, SPM '06, 219–228. Association for Computing Machinery, New York, NY, USA. doi:10.1145/1128888.1128919. URL `https://doi.org/10.1145/1128888.1128919`.

Lv, N., Jiang, Z., Huang, Y., Meng, X., Meenakshisundaram, G., and Peng, J. (2018). Generic content-based retrieval of marker-based motion capture data. *IEEE Transactions on Visualization and Computer Graphics*, 24(6), 1969–1982. doi:10.1109/TVCG.2017.2702620.

Mohammed, A., Schmidt, B., and Wang, L. (2017). Active collision avoidance for human–robot collaboration driven by vision sensors. *International Journal of Computer Integrated Manufacturing*, 30(9), 970–980. doi: 10.1080/0951192X.2016.1268269.

Müller, R., Vette, M., and Mailahn, O. (2016). Process-oriented task assignment for assembly processes with human-robot interaction. *Procedia CIRP*, 44, 210–215.

Safeea, M. and Neto, P. (2019). Minimum distance calculation using laser scanner and imus for safe human-robot interaction. *Robotics and Computer-Integrated Manufacturing*, 58, 33–42. doi: https://doi.org/10.1016/j.rcim.2019.01.008.

Scimmi, L.S., Melchiorre, M., Troise, M., Mauro, S., and Pastorelli, S. (2021). A practical and effective layout for a safe human-robot collaborative assembly task. *Applied Sciences*, 11(4). doi:10.3390/app11041763. URL `https://www.mdpi.com/2076-3417/11/4/1763`.

Scoccia, C., Palmieri, G., Palpacelli, M.C., and Callegari, M. (2021). Real-time strategy for obstacle avoidance in redundant manipulators. In V. Niola and A. Gasparetto (eds.), *Advances in Italian Mechanism Science*, 278–285. Springer International Publishing, Cham.

Tseng, M.M., Jiao, J., and Merchant, M.E. (1996). Design for mass customization. *CIRP Annals*, 45(1), 153–156. doi:https://doi.org/10.1016/S0007-8506(07)63036-4.