A Review of Safety Methods for Human-robot Collaboration and a Proposed Novel Approach

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Keywords: Obstacle Avoidance, Trajectory Planning, Sensory Systems, Environment Mapping, Serial Manipulators.

Abstract: Industrial robots offer the advantage of flexible manufacturing and increased efficiency when paired with human workers. However, this means breaking well-established safety procedures such as safety fences and workspace separation. Robots present a danger to humans as they work at high speeds with sudden motions. It is therefore necessary to ensure safe interaction during collaboration. This paper presents a collection of sources that explain the trends and advances in the field of industrial robotics specifically to safety in human-robot interaction. Major trends and popular methods lean towards obstacle avoidance using a sensory planning method of polynomials and a sensory system that is able to map the robot workspace. The goal of these methods is to ensure that the human is kept safe. These methods were used to develop a novel approach to safe interactions. This approach uses a LIDAR sensor for obstacle detection and tracking.

1 INTRODUCTION

Industry 4.0 has brought with it advances and advantages to factories and their methods of production specifically in flexible and reconfigurable manufacturing (Shiyong Wang, 2016). Industrial Robots perform a variety of repeatable tasks at consistent quality resulting in decreased waste and production costs (Fryman and Matthias, 2012). Factories are able to increase their production rate and throughput of components that meet all the quality standards leaving the humans to perform more complex tasks. However, the flexibility of robot systems is limited by programming and part feeding challenges. A human worker resolves this challenge by monitoring or working collaboratively with the robot. Humans perform maintenance tasks, check the quality of parts and set up the workspace of the robots. This close working relationship requires the robot to be aware of the human in its workspace.

Industrial robots are made of steel, are extremely heavy and move at high speeds with sudden movements. Without safety fences, these characteristics make it dangerous for a human to be in close proximity to an industrial robot as it performs its tasks (D. Gao, 2009). The human could easily be injured or killed by being hit with the robot arm or struck with the work tool. To ensure human safety, research is being conducted to discover ways of keeping humans safe within a robot production environment.

This paper presents the various safety methods used in industry as well as approaches developed by researchers. These methods are in accordance with ISO/TS 15066:2016 which are the methods of collaborative robotics. The safety method themes presented in this paper are robot vision, obstacle detection, obstacle avoidance, and trajectory planning.

A novel approach to safe Human Robot Interaction is discussed. The objectives of this research study were to research human-robot interaction, develop a sensory system for human detection, algorithms for data processing and predicting the location of the human in the workspace and to develop algorithms that allow the robot to modify its work routine in a safe, reactive manner. This paper contribution is a literature review of the state of the art methods of safety for humans in industrial robot production environments. The objective of safe interaction is to eliminate the risk of collisions between the human and the robot.

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2 COLLABORATIVE ROBOT SAFETY METHODS

ISO/TS 15066:2016, the technical standard for Human-Robot Interaction, states the basic safety methods of collaborative robots for industrial application. These methods are Hand Guiding, Speed and Separation Monitoring, Power and Force Limiting and Safety Rated Monitored Stop (Marvel, 2017). Hand Guiding allows the operator to transmit motion commands by showing the robot physically how to move when performing a task. The speed and separation monitoring condition continually monitors the proximity of the robot to the obstacle and maintains a set distance away. This condition is the most usable with regards to collision avoidance. The safety monitored stop condition stops the robot before the human enters the workspace. This can be implemented as a trip switch when a human enters the environment. Power and Force limiting is used to ensure that the force felt by a human worker is very small and does not injure the human in any way.

Industrial application collaborative robots have been developed by companies such as Rethink Robotics, Fanuc, Kuka, and ABB.

Rethink Robotics collaborative robot sawyer is a high-performance single arm robot designed to work on tasks that require high precision. Sawyer is a fully integrated collaborative robot solution, embedded with Cognex Vision System located in its arm. The vision system combined with built-in force sensors allow the robot to make adaptive decisions and work precisely $\pm$ 1mm away from the human for safe collaborative operation. Elastic actuators on each joint minimise contact force(robotics, 2017). The sawyer robot uses the Speed and Separation monitoring and the Power and Force Limiting safety method.

Fanuc's collaborative model cr-35ia is aware of its surroundings and stops safely when contact with a human operator is detected. The Dual Check Safety system can be set up to perform checks on Position, Safe Zones, Speed and Cartesian Position. This system decreases the amount of floor space needs for safe operation and eliminates the need for fences(Robotics, 2019). This robot also used the Power and Force Limiting safety method of Human Robot Collaboration.

Kuka LBR iiwa (intelligent industrial work assistant) robot has been designed for close human collaboration. This robot is light weight and able to react quickly if human contact is detected by its joint torque sensors(KUKA, 2014). Kuka LBR iiwa uses the Power and Force Limiting technique.

ABB's robot Roberta is a collaborative robot designed to suit Small to medium size enterprises. This agile, light weight robot features a camera vision system that can detect the object in its gripper and is able to decipher if it is a human hand or a tool. It is also equipped with fingertip force sensors that slows down or stops the robot when contact is detected with a human(Robotiq, 2014). Roberta uses the Hand Guiding and Power and Force Limiting techniques.

3 ROBOT VISION

To perform obstacle avoiding tasks the robot requires complete awareness of its workspace and any potential obstacles in the field. Robot awareness is created by implementing a vision system that covers the entire workspace. Vision systems such as stereo cameras, RGB Vision systems, proximity sensors and ultrasonic sensors provide decent awareness of the robot workspace environment. The sensors detect the presence of an obstacle in the environment. Obstacle tracking data provides information about human intention. This is achieved by tracking and interpreting human motions and gestures (Billard and Dillmann, 2006).

The workspace is created using grid representation. The location of an obstacle within the grid is communicated to the robot to facilitate obstacle avoidance and trajectory planning. Constructive solid geometry is primarily used to model the robot workspace environment (Zacharias et al., 2007).

Localisation and position are primarily based on visual and positional data derived from the visual sensors of the robot. There are two approaches that exist: Continuous geometric mapping and Discrete cell-based mapping. Continuous geometric mapping represents the environment more accurately, while Discrete cell-based mapping method represents the environment in discrete cells that form a grid. Each cell represents a square area of the environment and stores a value that indicates the occupied state of that area. (Marvel, 2017)

4 ROBOT CONTROL

Robot control is essential to ensure the robot performs appropriate actions around humans in the workspace and completes tasks while avoiding all collisions. It is necessary for the robot to be programmable in order to achieve a variety of tasks. Adaptability is also necessary for the robot to modify its own behaviour, meet its goal and have good reactivity to sudden obstacles (Albu-Schäeffer et al., 2005).

4.1 Obstacle Detection

Obstacles within the workspace can be detected by proximity or depth sensors. Ultrasonic sensors emit an ultrasonic sound wave and receive the echo. The time taken for the echo to return can be used to calculate the distance of an obstacle away from the sensor. Other sensors such as stereoscopic sensors use 3D imaging to create the illusion of depth offering the advantage of depth perception of the environment (Pérez et al., 2016). Infrared Sensors detect motion of a human in the workspace and can only be used for dynamic objects.

Capacitive sensors are used to detect the presence of a human. These sensors are capacitors that detect and track a human with good accuracy. The robot manufactures at Fogale Robotics have used this technology to create a skin that covers the robot to detect a human at any point on its body. Scanning range finders such as LIDAR or RADAR are capable of detecting an obstacle as well as counting, locating and tracking them. Cameras and imaging devises are the most popular form of obstacle detection and tracking in a robot workspace. They are also the most affordable to implement. A depth camera captures the depth of an object. A study by (Flacco et al., 2012) has shown that a robot can avoid an obstacle easily and consistently when using depth camera imaging.

4.2 Obstacle Avoidance

Obstacle avoidance algorithms instruct the robot to avoid a collision with a human and the path planning algorithm plans a new path to allow the manipulator to contour around the human towards its goal configuration. The kinematic calculations determine the position and orientation of the new goal pose once the path has been planned. Robot motion is restricted due to singularities. The path planner considers the singularities when planning the trajectory of the robot.

Real-time collision avoidance methods allow for safe human-robot interaction as the robot can adjust itself as the human moves within the workspace. A method described by (Fratu et al., 2010) continuously measures the proximity between the robot and dynamic obstacles and uses the data to generate repulsive vectors. The vectors control the robot as it manoeuvres and performs a task. An obstacle avoidance algorithm by (Flacco et al., 2012) uses a stereoscopic depth sensor to capture the environment. The obstacle avoidance algorithm incorporates different reactions that have been set up for the end effector and other joints of the manipulator. This allows the robot to react in a number of ways to avoid an obstacle.

To avoid collisions with dynamic objects, free space must be considered around these objects. Collision avoidance is an important factor in Path Planning. In a case where there is no automatic collision avoidance, the robotic workspace must be engineered to be collision-free another option is to have sub-optimal paths which are selected by the human programmer (Mohammed et al., 2017). The feedback to the planner is used to pause paths where collisions are imminent.

4.3 Trajectory Planning

Trajectory planning is fundamental to collision avoidance techniques. To re-rout a robot and avoid an obstacle the robot needs to search for a new path and plan a trajectory that will allow it to contour around the human and meet its goal without collision. The term trajectory refers to a path that is executed in a specific time interval. Trajectories can be planned using a variety of equations to specify the shape of the path. The most common being the polynomial trajectory. Polynomial trajectories are commonly formulated using a polynomial equation these equations are iterative and plot a spline when the time is specified. The coefficients calculated are the velocity, acceleration and position values for the trajectory (Letla, 2008). The degree of the polynomial depends upon the complexity of the path.

A study by (Boryga et al., 2015) has used a method called PR-RPT (Planning Rectilinear-Arc Polynomial Trajectory) which is a method of trajectory planning that links rectilinear lines that intersect with a curve of a set radius. This method uses a seven-degree polynomial so that the jerk is equal to 0 when the robot transitions between speeds. Seven types of path planners exist. These include knowledge-based simple path planners, knowledge-based hybrid path planners, sensor-based path planners, static knowledge and sensor-based hierarchical path planners, dynamic knowledge and sensor-based path planners, path planners based on offline programming, path planners based on online programming.

4.4 Trajectory Planning Methods

There are three types of trajectory planning algorithms: road map, cell decomposition and potential field method. The road map method represents the free configuration space and its connectivity to other free paths. Cell decomposition can be broken down into two aspects: exact cell decomposition and approximated cell decomposition. The Octree method is an approximated cell decomposition method where the cells are consecutively subdivided until there are no mixed cells on the map (Sousa e Silva et al., 2013). A paper by (Barcellini et al., 2012) defines a virtual wall around an obstacle where a robot senses repulsive forces which signal it to turn away from the obstacle. The potential field method is the earliest and most popular method used for obstacle avoidance. This method is implemented by defining a potential field of repulsive forces around the obstacle in the workspace. The robot is able to sense this method and adjust its posture to avoid the obstacle in the field. Combining octree and potential field methods, the manipulator is repelled by the obstacle and attracted towards the goal configuration.

A study by (Leutert et al., 2012) implemented Photonic Mixer Device that gathered depth information of the robot environment. This information was used to build an environment model which served as an input for the path planning model. The robot uses the data to autonomously select a path to navigate towards the target position while avoiding all static, dynamic and obstacles and continuously optimising its trajectory.

A study by (Nieto et al., 2010) uses the RRT (Rapidly-exploring Random Tree) method to plan a path in a dynamic environment. New paths are planned based on the mapped area of the robot workspace. The main aspect of this research is centred around an approach to formulating a cost function for a motion planner for human-robot collaboration. This method quantifies the consistency of the robot's motion so that it is predictable. (Mišeikis et al., 2016) developed an algorithm that avoids a human using lane differentiation. The robot and human are represented in separate lanes and the robot avoids the human without collision while considering its tasks. This method was adapted from aeronautic planes avoiding each other on runways. Shorter and smoother trajectories where produced when compared to reactive trajectory planning. A method by (Jin et al., 2005) avoid obstacles while positioning the end effector with on-line line collision avoidance. The motion planning method is sensor based and operates around unknown obstacles of arbitrary shape. This method is an online collision avoidance method that requires no prior knowledge of the obstacles. A trajectory scaling algorithm for safe Human-Robot Interaction that relies on a real-time prediction of human occupancy was developed by (Eder, 2014). By knowing the space that the human will occupy and the robots stopping time, the controller is able to scale the manipulator's velocity for safe interaction.

4.5 Pre Collision Methods

Pre Collision methods are considered as preventative methods and are intended to ensure safety during Human-Robot Interaction. These methods are implemented by monitoring the human and the robot and then adjusting the robot controller according to the feedback. The most common techniques and methods are Quantitative Limits, Speed and separation Monitoring and Potential Field Methods. Quantitative Limits are described as a guarantee that a robot cannot pose any threat to a human even if a collision occurs. This is done by limiting parameters such as joint velocity, energy and potential exertion of force (Lasota et al., 2017).

When there is no human presence in the workspace the motion can be maintained at the maximum programmed speed. At this point, all tasks and actions are taken as autonomous state behaviour. When a human enters the workspace and is detected by the robot the collaborative behaviour is activated. The distance from the human to the robot manipulator arm is constantly monitored. As the human approaches the robot, the safety constraints cannot be guaranteed while maintaining the production at maximum level. The robot reduces its speed and modifies its behaviour accordingly. If the robot comes to a point where it could collide with the human, the robot stopped. This should happen at 0 speed as the human is almost in contact with the manipulator (Zanchettin et al., 2016).

5 SAFETY IN HUMAN-ROBOT INTERACTION

This study contributes to the design of algorithms for safe human-robot interaction. The proposed approach is to develop a sensory system to detect humans in the workspace of a robot and develop obstacle avoidance and trajectory planning algorithms. The project will be developed as described in Figure 1.

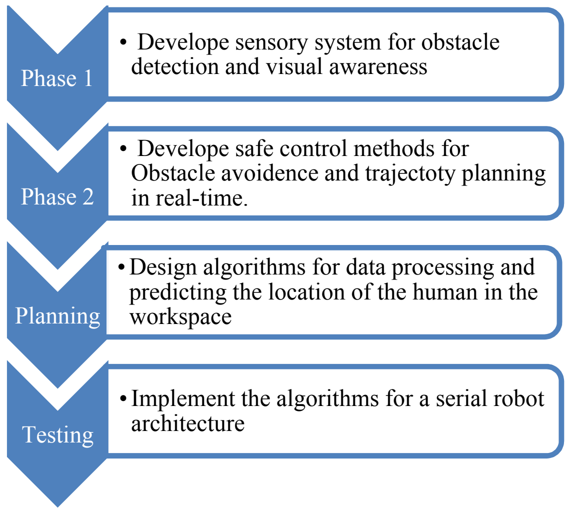

Figure 1: Development of Research Project.

This novel approach uses a LIDAR sensor. The LIDAR model that will be used is a Garmin v3 Lite. This sensor has a range of 10mm to 40m and a frequency of 50 to 500Hz (Garmin, 2016). The LIDAR is mounted on a pan-tilt mechanism to detect the presence of humans in the workspace. The LIDAR sends and receives a laser signal. When connected to a microcontroller the distance data is displayed as a 3D point cloud. When a human is less than the specified distance away from the robot, the robot will slow down and begin planning a new trajectory. This approach is unique as LIDARs are traditionally used to detect and track humans and objects for mobile robotic applications. For this case, it will be applied to a serial industrial robot application.

The pan-tilt motion of the mechanism is created using servo motors. The servo motor position is fed into the control system and the location of the obstacle is found using trigonometry.

The kinematics of the robot is calculated using Peter Cork's Toolbox. The algorithms will be implemented on a six degree of freedom serial arm industrial robot.

The environment will be modelled using an octree. This method allows for fast path planning and obstacle avoidance. The octree indexes three-dimensional space such that the occupied state of each region can be determined.

The path planning module will apply the A* search algorithm in combination with local Hill Climb and Simulated Annealing. This combination was found to be most efficient by (Leutert et al., 2012) The planner operates by searching for a path from the starting position to the goal position using partial local search algorithms. If no path is found the planner uses the complete A* algorithm with a modified distance estimator. The A* algorithm also avoids singularities in the robot's architecture. The obstacle will be bound by a bounding volume represented by geometric objects. When a robot coincides with the bounding volume, the robot is too close to the object and a new path should be planned.

The calculations, instructions, commands, detection, mapping, path selection will be calculated and simulated on MATLAB using Peter Corke's Toolbox. The virtual implementation allows safe testing before the algorithms are implemented in a real-world scenario. Peter Corke's Toolbox will be used as a solver to perform all kinematics calculations. The proposed architecture setup is presented in Figure 2.

This project addresses the issue of human safety when working within the workspace of a robot. The algorithm combination makes for suitable pathfinding and obstacle avoidance. It is fast and accurate providing reliable results. This method will ensure that safety of the human in the robot workspace.

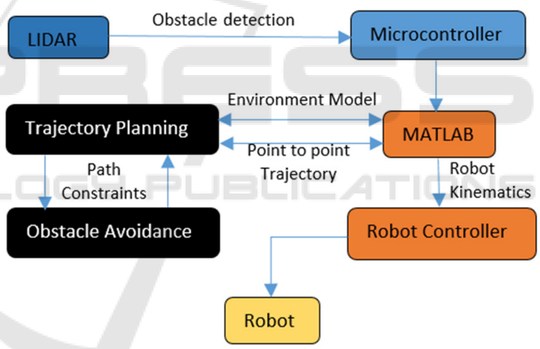

Figure 2: Proposed Architecture Setup.

6 CONCLUSION

Autonomous factories are advancing swiftly with more robots being implemented without fences. With humans working in close proximity to the robot, it is important to ensure that there are no injuries or fatalities. A method of robot awareness and reactivity are essential to ensuring safety. Visual systems notify the robot of a human presence in its workspace. Control systems allow the robot to adjust its path and to avoid the human and generate a new path towards its goal. The proposed method of obstacle avoidance and trajectory planning will be tested and validated. This method combines octrees and A* algorithm with local Hill Climb and Simulated Annealing for reliable obstacle avoidance and trajectory planning.

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