

Collision Monitoring for a Mobile Manipulator Based on Biologically-Inspired Dynamical Systems for Movement Generation

Sreenivasa Hikkal Venugopala, Zain Ul Haq, and Urvashi Negi

Advisor: Djordje Vukcevic

Abstract—The computations involving the robotic manipulators, that is robotic arms and the mobile manipulators, that is mobile base (robot base) up until recent times are limited in the degree of operation and have several restrictions due to rigid movements, the control algorithms for these manipulators are usually complex involving various operations such as planning, perception, and so on. This makes the computations complex and time consuming and make it hard for its usage in the dynamic environments involving other robots, humans. To overcome these issues, in this research work, we propose to extend the implementation of the control algorithms which is implemented based on collision monitoring [?] and collision avoidance [?] for controlling the movements of the robotic arms from colliding each other and to extend it to avoid collision with the mobile base as well. Along with this, we also implement the control algorithms for mobile base that helps in monitoring and avoiding the collision with any obstacles and helps in safe maneuvering towards the goal.

I. INTRODUCTION

The robotic arms or the robotic manipulators are used in various applications ranging from industrial applications to domestic applications. They are widely used in industrial applications such as to support human in the production lines of heavy machineries for the purpose of assembling spare parts, welding, painting and so on, and in domestic applications such as robotic prosthetics, robotic assistants, and so on. Along with these applications, A robot as a whole, that is including both arms and the mobile base, poses useful in various applications such as warehouse management. All these applications require more robust and highly adaptable software and hardware components. For increasing the efficiency and the robustness of the functioning of the robotic manipulators in industrial applications, a precomputed trajectories will be provided [?], but these precomputed trajectories will not consider the dynamic movement of human and other obstacles. On the other hand, various operators are used to control the movement and functioning of the robotic prosthetics, but this does not provide free flow motion for the arms or prosthetics. On contrary it takes a lot of time and effort to train the robotic manipulators to perform a safe and free flow movement, but this is a high cost solution which is not weighable in all scenarios.

One of the solution approach to handle the control algorithm problem is to make use of the dynamic movement primitives, these are generated during the movement of the robot manipulators resulting in real-time collision monitoring and avoidance. There were many approaches proposed as a solution to this problem, based on the approaches proposed by [?] and [?] a library named ‘Implementation

of biologically-inspired dynamical systems for movement generation: automatic real-time goal adaptation and obstacle avoidance’ was developed (https://github.com/HBRS-SDP/sdp_ss20_collision_monitoring_for_robotic_manipulators). This library handles the collision monitoring and collision avoidance for robotic arms in real-time and it incorporates the idea of dynamic movement primitives and the potential field method for active collision monitoring and avoidance. Here the dynamic primitives and the obstacles are considered as the basic primitives having shape and volume.

In this work, we propose to implement and extend the previous work by formulating the mobile manipulator or the robot base as a 3D box shape and extend the control algorithm to avoid and monitor the collision between the robot arms and its base. Along with this we also implement the control algorithm for the base to avoid and monitor the base from colliding with other obstacles. Initially we planned and tried to model the base as a convex hull using the approach proposed by [?], and it turned out to be complex and cost ineffective for this application. To overcome this, we modeled the robot base to be a 3D box and calculate the distance between other dynamic primitives which are discussed in the future sections. Extension of previous work to monitor and avoid collision between the arms and the base, along with implementation of the control algorithm for controlling the base from avoiding and active monitoring of collision makes the robot more robust, adaptable, and safe to use in dynamic environments including for domestic purposes.

This report is further structured as follows. Section 2 describes modeling and calculating the distances between the dynamic primitives, Section 3 highlights the implementation details, Section 4 describes various experiments conducted, and Section 5 provides information on use cases followed by the conclusion.

II. APPROACH

A. Distance between primitives

In previous work, the links and joints, along with the end-effector and obstacles were modeled as spheres and cylinders. In this work, along with the previous implementations, we model the robot base as a 3D box, this helps in easier calculations for the distance between the arms and robot body, and robot body and other obstacles. Following we will discuss the distance calculations between various primitive objects.

1) Distance between two spheres: We calculate distance between two spheres using below formula:

$$Distance = |\bar{C}_1 - \bar{C}_2| - (r_1 + r_2) \quad (1)$$

where \bar{C}_1 and \bar{C}_2 represent the center points of the two spheres, and r_1 and r_2 are the radius the two spheres.

2) Distance between sphere and cylinder: We calculate the distance between the sphere and a cylinder using below equation and the same is shown in the Figure ??.

$$Closestpoint = X = \begin{cases} x = x_1 + \lambda(x_2 - x_1) \\ y = y_1 + \lambda(y_2 - y_1) \\ z = z_1 + \lambda(z_2 - z_1) \end{cases} \quad (2)$$

$$\lambda = \frac{(c - m_1) \cdot (m_2 - m_1)}{La^2} \quad (3)$$

$$Distance = |X - C| - (r_a + r_s) \quad (4)$$

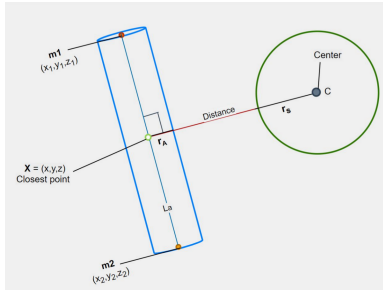


Fig. 1: Sphere - capsule

3) Distance between two cylinders: We compute the distance between the two cylinders based on the following four cases:

- 1) m1 and m2 can be perpendicularly projected on to La.
- 2) m1 and m2 cannot be perpendicularly projected on to La.
- 3) Only m2 can be perpendicularly projected on to La.
- 4) Only m1 can be perpendicularly projected on to La.

Here, m1 and m2 refers to the starting point and end point of the symmetrical axis of shorter cylinder, La is the symmetrical axis of the longer cylinder. This is shown in Figure ??.

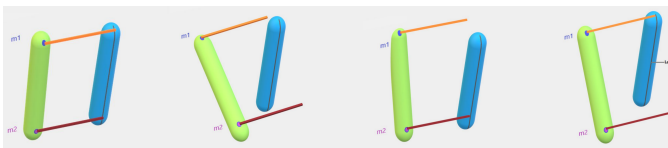


Fig. 2: Cylinder - cylinder

4) Distance between box and sphere: NEED TO FILL THE DETAILS

5) Distance between box and cylinder: NEED TO FILL THE DETAILS

B. Potential field calculations

In previous work, to avoid and monitor the collision between the robotic arms and the obstacles, the algorithm from [?] is implemented. This algorithm is based on the dynamic movement primitives (DMP) and is used to generate the new trajectories and velocities in real-time as given in below equations,

$$\dot{v} = K(g - x) - Dv - K(g - x_0)s + Kf(s) + p(x, v) \quad (5)$$

Where g is goal position, x is current position, x_0 is starting position, v is current velocity, s is phase variable, D is damping constant, and K is spring constant. The term $p(x, v)$ refers to the potential field generated by the obstacles which in turn helps in avoiding obstacles.

This potential field is calculated by determining the steering angle (Figure ??) between the velocity vector and the vector from the obstacle to the end effector as shown in ??. This steering angle provides information on the sharpness of the steering of end effector from obstacle. Using this angle, the potential field is calculated as given in Equation ??.

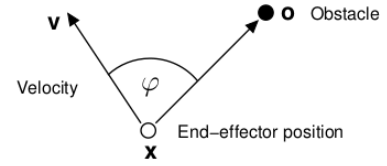


Fig. 3: Graphical representation of steering angle [?]

$$\phi = \cos^{-1} \left(\frac{(o - v)^T v}{\|o - x\| \cdot \|v\|} \right) \quad (6)$$

$$p(x, v) = \gamma \sum_i R_i v \phi_i \exp(-\beta \phi_i) \quad (7)$$

Where γ and β are tune-able constants, and R is a rotation matrix which rotates by the axis $r = (o - x) \times v$ with an angle of rotation of $\pi/2$. This rotation matrix can be calculated using the following approach described in [?]. The final potential field is the sum of the potential fields generated by all the obstacles. The final equation converges towards the goal avoiding the obstacles as given below.

$$\dot{v} = K(g - x) - Dv + p(x, v) \quad (8)$$

ADD INFORMATION ON POTENTIAL FIELD CALCULATION FOR MOBILE BASE

C. Collision monitoring library

This work is an extension of the the previous work. Here along with the robot arms from previous implementation, we also model the robot base such that the arms do not collide with the base while performing some actions. Along with this extension, we also implemented the base control algorithm which actively helps in monitoring and avoiding collision between the robot base and other obstacles in the workspace.

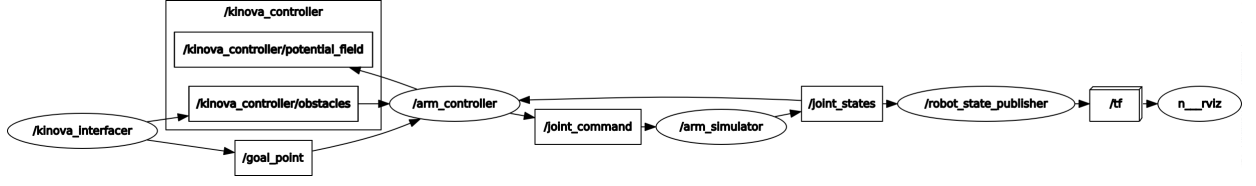


Fig. 4: ROS node graph for single arm

In order to monitor the distance between the links of the robot arm, obstacles, robot base in the workspace, the links are modeled as the cylinders, end effectors are modeled as spheres, and the robot base is modeled as the 3D box. This type of modeling helps in easier calculations of distance between two primitives which results in monitoring of the self collision of the arms and base. This kind of modeling helps in easier calculation of potential fields, determining the nearest points or closest points on the primitives and obstacles that helps in calculating the distances, which in turn results in real-time collision monitoring and avoidance.

ADD EXTRA CONTENT IF REQUIRED.

D. Controller

In this work, we follow the same architecture for the base controller as the previous work. Since we perform the collision monitoring and avoidance between the arms and the base, both the arm controller and the base controller are necessary. As per the previous work, the arm controller is controlled via a control loop which executes at a specific rate which provides the geometric locations and updates the velocity of the arms in real-time. Similarly, the base controller also controlled via a control loop which executes at a specific rate and provides information on the geometric location of the mobile base and the velocity updates. This real-time information on the positions of arm and the base helps in quicker calculation of distances and helps in collision avoidance and monitoring with self and other obstacles in the workspace.

ADD EXTRA CONTENT IF REQUIRED.

III. IMPLEMENTATION

The final product that combines all the obstacle monitoring and avoidance techniques was implemented using the Robotic operating system (ROS) framework, specifically ROS Kinetic. ROS has a few advantages in this area, the first and foremost being the Kinova Kortex library [?], which is a high and low level control API for Kinova robotic manipulators, including the one chosen for demonstration. This library has a lot of useful features from the MoveIt control algorithm to the fully fledged gazebo simulation of the arm. The final software produced does actually rely on any of the Kortex libraries, but was instrumental in testing and development.

The ROS package can be broken down into 3 sections, the controller, simulator and visualisation. The control section is the implementation of Biologically-inspired dynamical

systems for movement generation [?], the collision avoidance library is implemented inside a control loop that uses the monitor class to obtain the shortest distance vectors from the obstacles to the end-effector. This shortest distance is then passed into the potential field method along with the current velocity of the manipulator. From this the new velocity is derived and then passed into the simulator via an inverse kinematics function of the KinovaArm class, mapping the velocity from cartesian space to the manipulators joint space.

The simulation software takes the joint velocities from the controller and updates the current state of the simulated manipulator, and then passes the current state back to the controller as well as forwards to the visualisation. The simulation algorithm it's self is very basic and is based around a discrete time integration technique:

$$\theta_i = \theta_{i-1} + \dot{\theta}_{i-1} \times (t_i - t_{i-1})$$

While rudimentary, as it doesn't consider inertia or any other complex parameters, it functions as desired for the testing and demonstration of a robotic manipulators trajectory control algorithm.

The basic ROS node graph can be seen in figure ?? where the interfacier is a basic terminal interface to send goals to the arm controller and the visualisation is performed by the built-in robot_state_publisher node and Rviz.

IV. EXPERIMENTS

ADD INFORMATION ON THE EXPERIMENTS AND TESTS PERFORMED.

A. Collision Monitoring

The collision monitoring library has no practical measure of accuracy because of its pure mathematical basis. To assert the accuracy of the mathematics applied the distance between objects was verified using Geogebra models, and the rest of the software relies on those calculations. So the core performance measure of the collision monitoring library can be considered speed, hence the use of C++ instead of a higher level interpreted language like python. The performance test was performed on an Ubuntu 16.04 machine with a Intel Core i5-7200U 2.5GHz CPU. The following operations were timed using the C++ chrono library:

- The joint initialisation of one KinovaArm and Monitor class.
- The combination of initialising a Sphere and adding it to the Monitor class.

- The updatePose function, which updates the internal kinematic representation of the arm.
- The distanceToObjects function, calculating the distance from each of the manipulators links to the obstacle.
- The distanceBetweenArmLinks function, measuring the distance from each of the links to the other links in the same manipulator.

1) *Results:* Each operation was performed 100 times with a single spherical obstacle and mean calculated to produce the final results given in Table ?? below.

Operation	Time (seconds)
Init arm and monitor	0.00103831
Init and add object	0.00000276
Update the arm position	0.00012871
Distance to obstacle	0.00026022
Distance to self links	0.00199209

TABLE I: Execution times for collision monitoring tasks

From a cursory glance it is clear that the functions are quite fast, all operations take less than two milliseconds to complete, but some of the operations are not as fast as desired. From a runtime perspective the initialisation operations are not that important when it comes to overall speed, since they tend to only be run at the start of the program, and potentially at random intervals the program in the case of the obstacle initialisation. The distance to obstacles, distance between arm links, and the update function are the main operations relevant to the software refresh rate, these run every loop and depict the final update rate of the software. The update function of the arm is very fast, and the distance to obstacles function is the same only taking twice as long. It is important to note though that the time for distance to obstacles to execute relies on the number of obstacles, as the number of obstacles increases so does the time to calculate, in a linear fashion. This means that with 40 obstacles the software will be restricted to $\sim 10\text{Hz}$. Assuming only one obstacle the other large impact to overall performance in the distance to self links operation, taking up over four times the time used by the other two core functions combined. This was somewhat expected, if not to this extent, since the software was designed for portability in mind, which limits the possible optimisations available, still further investigation into the limiting factors should be performed. The final core loop time for the collision monitoring library is a little over 4.7 milliseconds, which would give a update rate of $\sim 250\text{hz}$, but this would gain significant benefits from the exclusion of the distance to own links monitoring functions.

B. Single arm obstacle avoidance

To assess the effectiveness of the algorithm we place several obstacles in the vicinity of the manipulator, and then command it to move between points in the workspace. First, we used the same set of obstacles, initial point and goal point for two experiments with two different values for γ as seen in Figure 4. When $\gamma = 0$ there is no influence of the potential field in the velocity, hence the end effector does not

avoid the obstacle. Whereas when $\gamma = 35$ the effect of the potential field steers the end effector away from the obstacle in its path. From these results we can assess that the DMP will converge to the goal point, and the value of γ has an impact in the effectiveness of the algorithm.

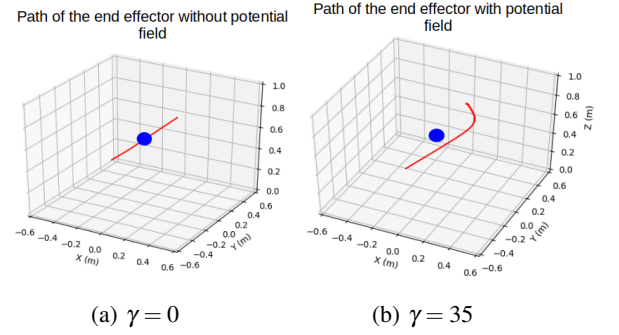


Fig. 5: Movement with different values for γ

In Figure ?? we can observe the behaviour of the potential field when several obstacles are nearby. Note that the potential field's magnitude is larger when the end effector is approaching the obstacles and gets smaller after it passes the obstacles. This is the effect of the steering angle, as when the end effector passes the obstacles the angle between the current velocity and the obstacles is large. It should also be noted that the direction of the potential field effect is not uniform between small steps.

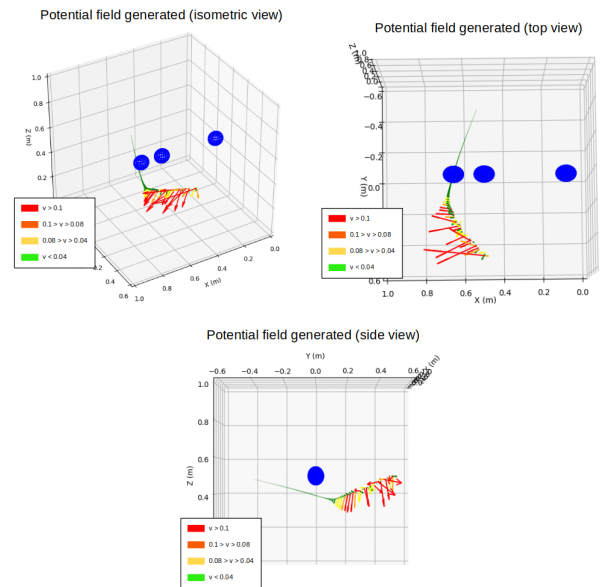


Fig. 6: Potential field generated during the movement

For one of the experiments we placed several obstacles in the workspace and command it to move between points. The results of the collision avoidance algorithm can be seen from several perspectives in fig ?? . The red line is the path of the end effector from the initial point to the goal. In fig ?? the velocity vectors in their respective point in time can be observed.

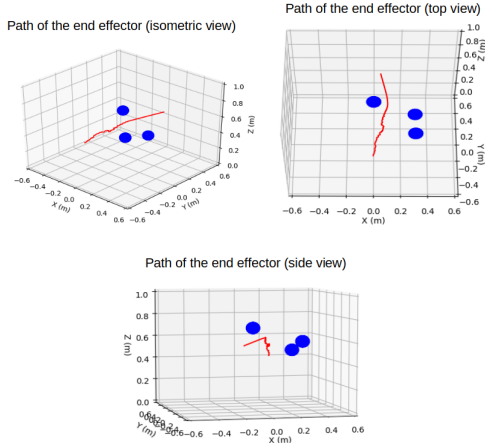


Fig. 7: Path of the end effector as it moves through obstacles

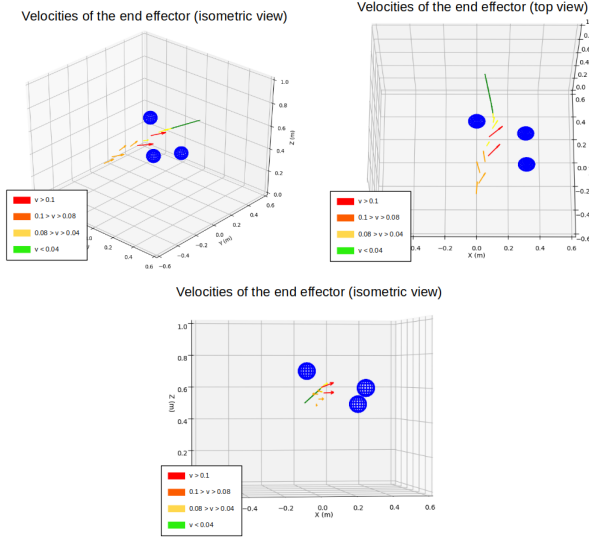


Fig. 8: Cartesian velocities generated by the algorithm

As it can be observed from Figure ?? and Figure ?? the collision avoidance algorithm can generate velocities that avoid several obstacles without problems.

C. Dual arm collision avoidance

In order for two manipulators to operate with intersecting workspaces it is important that they do not collide with each other. In this experiment we simulated two instances of the Kinova arm placed close to each other so their workspaces would overlap. Each arm is individually controlled, meaning we could place one arm on the path of the other to assess if

the arms avoided collisions. An example setup can be seen in Figure ?? . The objective is to assess if the arms avoid colliding with each other during operation.

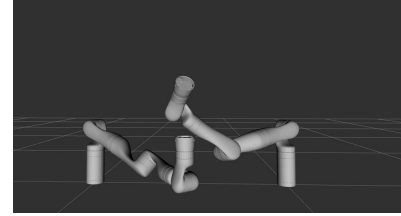


Fig. 9: Two arms sharing a space

In Figure ?? the path of the end effector of first Kinova arm can be seen as well as the pose of the second arm. The pose of the second arm remained constant during the movement of the first arm.

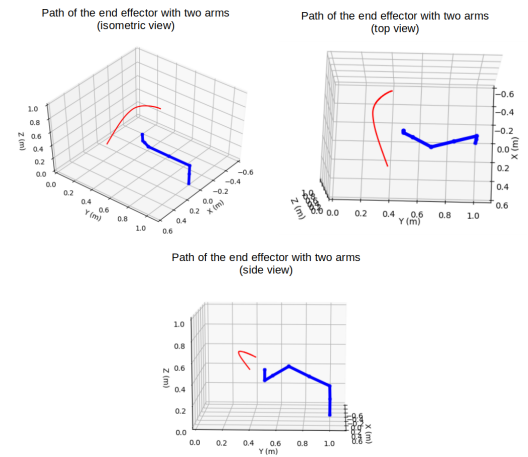


Fig. 10: Path of the end effector of one arm

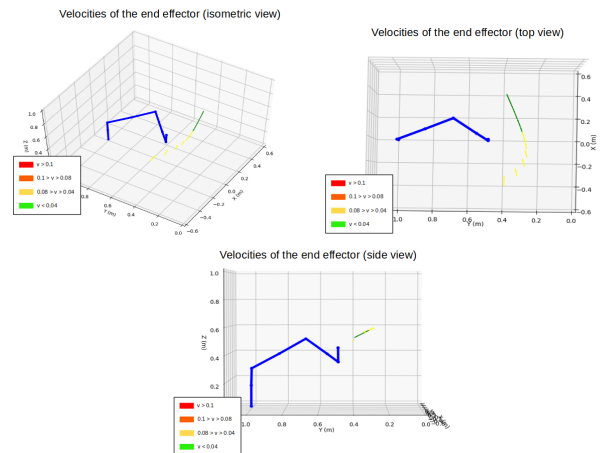


Fig. 11: Cartesian velocities generated

From these results we can see that as long as the geometric representation of the two arms is accurate, the collision avoidance algorithm can be used to avoid collisions between the arms. The collision avoidance algorithm only monitors the end effector of the moving robot, this means that not all collision between the two arms can be avoided. To fix this a null space control algorithm would need to be implemented.

V. USE CASES

A. Single arm

The library presented in this paper can be used with a single manipulator to avoid the collision of its end-effector with objects in the environment. The user can use the Arm interface to provide the necessary information about the manipulator. The user can then also add different obstacles that are present in the environment. The pose of the manipulator and the obstacles need to be updated using the methods given by the library.

B. Dual arm

The user can also use the library with two manipulators by creating two instances of the implementation of the Arm interface and adding the links of the opposite manipulator as obstacles represented by capsules. This will prevent the collision of the end-effector of both robots with the opposite manipulator.

C. Multiple arms

In the same way, the library can be used with more than two manipulators. The user can add as many manipulators as the computational resources allow.

D. Self collision

Finally, a user can also use this library to prevent the collision of the end-effector of the manipulator with its other links. This can be done by implementing the Arm interface and adding each link of the robot as an obstacle represented by a capsule.

VI. CONCLUSION

For robotic manipulators to be used in a human environment they first need to have the ability to adapt in constantly changing, dynamic environments. This can be done in a robust and safe manner using a combination of two different methods discussed by H. Hoffmann et al. [?] and O. Khatib [?]. By implementing the obstacle monitoring by O. Khatib [?] and the collision avoidance by H. Hoffmann et al. [?], along with monitoring collisions for all links, robotic manipulators are more resilient to changes in obstacle and goal placement. The final collision monitoring library can have an update rate of $\sim 200\text{Hz}$ with all features enabled, this is a viable update rate, but this would become drastically impacted if more than 10 obstacles were to be added to the environment. From the experiments it can be concluded that the DMPs used in this algorithm converge to the goal, and that the potential field term influences the end effector's path to steer away from obstacles. It can also be observed that the

effectiveness of the algorithm is dependent on the parameters of the DMP equation, hence it is important for a developer to fine tune these parameters until a certain level of performance is reached.

While the algorithm produced gives some significant benefits over previous methods, there is still a lot of potential improvements. The collision monitoring library could benefit greatly from some optimisation of the self collision functions, along with the addition of more shapes. The current shapes are a basic sphere and capsule, with the addition of an n-ellipsoid primitive a large majority of basic shapes and structures could be constructed by the combination of the primitives. Finally, in order to avoid more serious collisions, the algorithm should consider the entire body of the manipulator rather than just the end effector.

ACKNOWLEDGEMENTS

We would like to thank our supervisor Djordje Vukcevic for all the advice and help this semester.

REFERENCES

- [1] O. Khatib, Real-Time Obstacle Avoidance for Manipulators and Mobile Robots The International Journal of Robotics Research, vol. 5, no. 1, pp. 90-98, Mar. 1986, doi: 10.1177/027836498600500106.
- [2] H. Hoffmann, P. Pastor, D.-H. Park, and S. Schaal, Biologically-inspired dynamical systems for movement generation: Automatic real-time goal adaptation and obstacle avoidance, in 2009 IEEE International Conference on Robotics and Automation, Kobe, May 2009, pp. 2587-2592, doi: 10.1109/ROBOT.2009.5152423.
- [3] M. S. Fadali and A. Visioli, Introduction to Digital Control, in Digital Control Engineering, Elsevier, 2013, pp. 18.
- [4] S. Adey, Dean Kamens Luke Arm Prosthesis Readies for Clinical Trials - IEEE Spectrum, IEEE Spectrum: Technology, Engineering, and Science News, Feb. 01, 2008. <https://spectrum.ieee.org/biomedical/bionics/dean-kamens-luke-arm-prosthesis-readies-for-clinical-trials> (accessed Jun. 25, 2020).
- [5] F. Janabi-Sharifi and D. Vinke, Integration of the artificial potential field approach with simulated annealing for robot path planning, in Proceedings of 8th IEEE International Symposium on Intelligent Control, Aug. 1993, pp. 536-541, doi: 10.1109/ISIC.1993.397640.
- [6] Belongie, Serge. "Rodrigues' Rotation Formula." From MathWorld—A Wolfram Web Resource, created by Eric W. Weisstein. <https://mathworld.wolfram.com/RodriguesRotationFormula.html>
- [7] Kinovarobotics/ros_kortex. Kinova Robotics, 2020.
- [8] E. G. Gilbert, D. W. Johnson and S. S. Keerthi, "A fast procedure for computing the distance between complex objects in three-dimensional space," in IEEE Journal on Robotics and Automation, vol. 4, no. 2, pp. 193-203, April 1988, doi: 10.1109/56.2083.