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# **A study of cooperation between humans and robots in warehouse intersections**

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## **Abstract**

In the modern world, many warehouses use robots to collect different orders and to keep humans safe the robots work in restricted areas. This practice could be seen as a waste of space and resources. Therefore, this paper sets out to investigate whether it is time efficient or not. The study clocked 27 test subjects completing a simple task in a simulated environment alongside a robot, and compared the time against two robots completing the same tasks. The timer stopped when both parties had completed their task. The simulated environment consisted of an intersection and a script making the robot give way to the human-navigated robot. In the control environment with the two robots, hierarchical protocols were used, making the robot with less work left to give way to the other. The results of the study showed that it is more time efficient with only robots working in this simulated environment, compared to having both a human and a robot sharing work area. However, the results also showed that the human approach towards the robot affected the result. A test subject with a positive view on cooperating with the robot resulted in a shorter time spent on completing the task than test subjects not taking the robot into account. This could imply that it is possible to make the human-robot interaction more efficient by altering the human approach towards the robot.

## Sammanfattning

I dagens samhälle finns det många lager som använder robotar för att samla ihop olika ordrar. För att minimera risken för olyckor med människor arbetar robotarna ofta i avgränsade områden. Det kan anses vara ett slöseri på utrymme och resurser. Därför kommer denna rapport att undersöka om det istället är tidseffektivt eller inte. Studien tog tiden på när 27 stycken försökspersoner utförde en enkel uppgift i en simulerad miljö, vid sidan av en robot, och jämförde tiden det tog för två robotar att utföra samma uppgift. Tiden stannade när båda parter hade utfört sin uppgift. Den skapta miljön innehöll en fyrvägs korsning och ett skript som gjorde så att roboten lämnade företräde för den människostyrda roboten. I miljön med de två robotarna används hierarkiska protokoll som gjorde att roboten med minst arbete kvar lämnade företräde för den andra roboten. Studiens resultat visade på att det är mer tidseffektivt med endast robotar som arbetar i denna simulerade miljö, jämfört med att ha både en människa och en robot som delar på arbetsytan. Däremot så visade resultatet även att människans inställning till roboten påverkade resultatet. En försöksperson med en positiv inställning till att samarbeta med roboten tog kortare tid på sig att utföra uppgiften jämfört med de försökspersoner som inte tog hänsyn till roboten. Detta kan implicera att det är möjligt att få en människa-robotinteraktion mer effektiv genom att ändra människans inställning till roboten.

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# Chapter 1

## Introduction

Humans have always tried to find easier ways to perform different tasks, ways that are less physically strenuous and more time efficient. One way to do so is through robotics, using a machine that can be programmed to accomplish the different assignments instead of relying on humans. By doing this, it is possible to minimize the time spent on each task and maximize the profit. Today, autonomous robots are used in many different industries. One example where they are frequently employed is warehouses, and one of their tasks could be to move and stack the different products in order to ship them to stores for example.

Using new technologies often brings new challenges that have to be analyzed and overcome. One of the challenges with autonomous robots in warehouses is collisions between a robot and another object, for example, another robot or a human being [1]. One solution to collisions between human beings and robots can be to have different areas in a warehouse where only robots are allowed to operate, which makes it safer for humans since many accidents happen because of human errors [2]. Another issue that arises here is the extra space taken by the separation of human beings and robots, which means that this solution is not space-efficient. However, it is not obvious if the separate working area approach is more time-efficient, compared to having human beings and robots working in the same area.

### 1.1 Problem statement

Does creating an environment where both robots and humans can work alongside one another enable a more time efficient work process? The focus of this report will be on a four-way intersection and the time it takes for two agents to pick up and transport a number of items from one side of the intersection to the opposite side. The study compares the time difference between two robots who can communicate operating the intersection versus a robot and a human being performing the same task.

### 1.2 Scope

This study mainly focuses on hierarchical protocols. Therefore, the research has a rather simple artificial intelligent implementation where the robots themselves analyze the situations and have a number of pre-set decisions that can be made based on the status.

A simulation was created of the two scenarios and used to provide insights to answer the question stated above, using a human controlled object to symbolize a human being during the simulation.

### 1.3 Outline

In Section 2, the focus will be on related work to review what has previously been discovered in the field of robotic time management and also what different methods that have been used. In Section 3, the method and tests performed in the study are described in detail. The results of the work are presented in section 3, followed by the Discussion, section 4, where the results and limitations are discussed and analyzed along with some suggestions for future research.

## Chapter 2

# Background

### 2.1 Terminology

The following are a few key concepts.

**Collision:** The definition of a collision is "simultaneous existence of another mobile object at the same position in the route of a mobile object" [3].

**Protocol:** A protocol is a set of rules which decide how the robot should act in different situations.

**Agent:** An agent signifies a moving object capable of making its own decisions, in this case, both humans and robots.

**Deadlock:** A Deadlock is a state where two or more agents are waiting on each other to take action and therefore unable to proceed without breaking a predefined rule [4].

### 2.2 Pre-planned paths

Pre-planned paths are meant for robots who cannot move freely. They are restricted to certain movements, for example following lines on the floor.[1] This example can be visualized by seeing the movements as very similar to how a train must follow its tracks. In the case of the following lines, they can change their movements as long as they stay on their "tracks". One way of avoiding collisions could be to have robots start with intervals that would stop their occurrence from colliding when their paths cross.

### 2.3 Collision zones

The first part that will be introduced is collision zones. The idea of having a specific zone as collision zones is to minimize these expected collisions as much as possible. An example that suits this case is creating them at intersections where the robots are most likely to collide. This is done by having an area around the intersection marked as a collision zone. One way that collisions are avoided is to make sure that only one robot can enter the collision zone at the same time[1]. There are many ways of making these decisions, one such way is to write collision avoidance protocols. These protocols will be presented below in 2.4.

The issue of having robots traverse collision areas at different times can be solved in many different ways. One solution is to let the robots have different starting times to reach the collision zones at different times, as mentioned above in 2.2 or to make the robots stop if they detect that the collision zone is already occupied by another agent [1].

### 2.4 Protocol

There are different ways to use protocols in a warehouse, one example is gates that choose which agent gets to pass depending on their priorities [5]. In some cases, the robots repeatedly perform the same task but the preferences or priorities change over time [6]. These priorities are decided in the protocol and when two robots meet the one with the highest priority gets to pass.



There are different types of protocols; for example local (where the robots do not exchange information) and global (where the robots are connected to a global communication network). In earlier warehouse solutions the lack of global communication networks restricted the possibilities of the protocols. These limitations made the choice of local protocols more suitable [7]. In the cases where the robots do not communicate, information is obtained in advance, such as maps or number of robots and is used as a base to create rules. This does not mean that they are not aware of each other but rather that they do not exchange information [3].

A protocol that stops the robot to avoid a collision can be implemented as one that is only affecting the speed controller of the agent. The mentioned speed controller pauses to stop the robot and un-pauses to continue along the path [8]. This is something that could be used when looking at having humans and robots move in the same area. Since human motions are very unpredictable they must possess a higher priority due to safety reasons. One way to accomplish this is to make the robots stop when approaching a human. Furthermore, humans have also been found to react in a frightened way when interacting with a robot, which can lead to human injury [9]. Unfortunately, it is not efficient to have robots stop to avoid collisions which is why effective stopping policies need to be introduced. Stopping policies mean that the protocols can take more information into account instead of operating naively, by forcing the robot to stop when the risk of a collision appears. In this case, the robots can individually decide if they should wait or go which would, for example, be decided mutually between the affected robots [1].

One way to solve collisions as introduced above is by using a global protocol. In the case of global protocols, global variables can be used to create locks. When a robot approaches a collision zone it will determine whether the zone is occupied and if so the global variable will be locked, hence the name lock, and this will block other agents from entering the collision zone. When the agent exits the collision zone the global variable is unlocked, unblocking the collision zone for other agents to enter again [10].

Deciding which robot has the highest priority can be done by considering many different optimization parameters and strategies. One parameter to take into account is which robot has the most tasks to perform. The efficiency wanted can then be reached by minimizing the time for the last agent to reach its goal [6]. The extra waiting time for each robot can also be taken into account when deciding which one that has to stop [6]. If they have the same priority one possible solution is to create a random selection strategy [1].

## 2.5 Intersections

An intersection in a warehouse is where two or more aisles meet. A proposed collision avoidance solution has been made with the assumption that collisions only occur at intersections. In this case, the robots also only move along their own path and cannot deviate from it. The collision will then only occur in the cases where agents travel along the crossing paths at the same time which would be at intersections [3]. This also makes it possible for the robots to only check for other agents at the intersections [3]. Although only having the risk of collisions at intersections makes the solution simpler, the possibility of agents getting stuck in a deadlock cannot be ignored [1].

## 2.6 Other related work

For a collision-free path to be planned in advance by using pre-planned paths it must almost be completely free of unpredicted obstacles. Humans moving in the same area could be seen as obstacles that could interfere with the pre-planned path and therefore make it impossible to follow the path. A better option, in this case, would be to have the path changed if an unpredicted obstacle is encountered at a collision area [1].

Another way of avoiding collision risks is to modify the path the robots follow so that the intersections they have to pass are fewer. Minimizing the number of collision zones on the path would make the risk of collisions smaller, but this would often mean that the path taken by the robot is longer or less effective making the execution time longer [10].

## Chapter 3

### Method

In this chapter, the method used to answer the problem statement of this paper is explained in detail. Figure 3.1 shows an overview of the simulated environment.

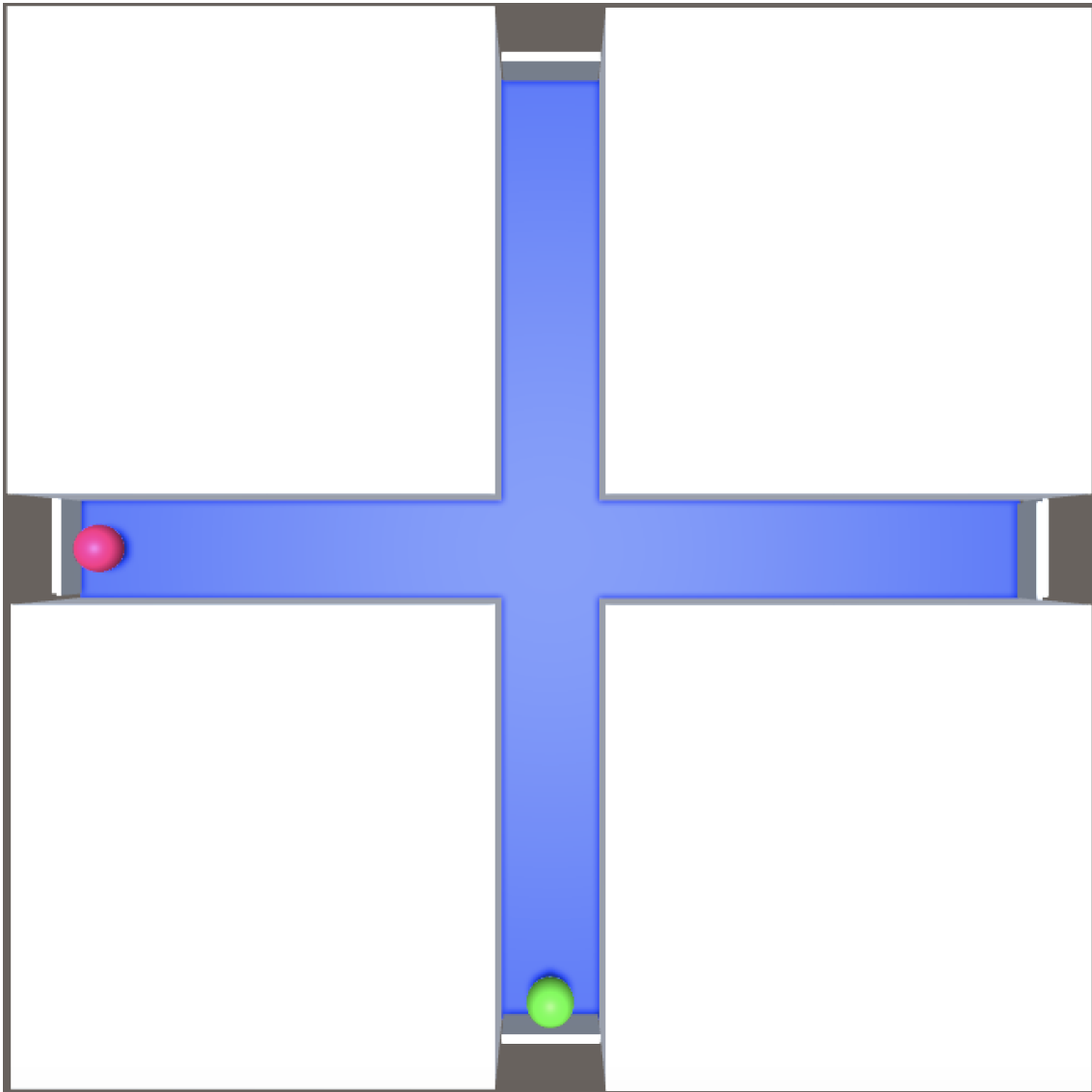


Figure 3.1: Overview of the simulation

## 3.1 Approach

We tested two different simulation scenarios and compared the total time it took to complete tasks in the scenarios. One scenario had two robots that simultaneously completed tasks and the other had one robot and one agent navigated by a human being, completing the same tasks as in the first scenario. The environment was a 4-way intersection where each agent started in one of the aisles, where it was supposed to touch a wall to pick up one object and then cross the intersection to touch another wall to place the object. These walls are the ones at the end of each aisle. Each agent performed this task five times, which meant that each agent had to cross the intersection at least nine times since both agents started at their pick-up stations. One test consisted of five identical tasks, where one task was to pick up and drop off one object. The robots are, as seen in Figure 3.1, modeled as two spheres; one green and one pink. The green sphere moved back and forth from south to north and the pink moved back and forth from east to west.

## 3.2 Environment

We created four white cubes to represent the walls in the warehouse. The space between these boxes created the blue aisles and the 4-way intersection. There was a white wall at the end of each aisle to represent a pick-up station or a drop-off station. When the agent touched the pick-up station a holding-variable updated to "true" and when the agent touched the drop-off station the variable changed to "false". The agent could only pick up an object if the holding-variable was "false" and it could only drop off an object if the variable was "true".

## 3.3 Unity

We used a tool called Unity to create the simulation of our warehouse (Figure 3.1). We wrote scripts including protocols in the programming language C#. We created the different objects and walls in Unity's modeling tool and then connected the C#-scripts to the different objects to control the movements and the protocols.

## 3.4 Game view

The tests were performed on a computer, and we showed different views on the screen depending on what scenario we were testing; the Human-Robot test or the Robot-Robot test. In this section, we will explain what was shown on the screen during the different scenarios and why.

### 3.4.1 Human - Robot game view

The unity environment was implemented with two views of the scene, and a start screen where the user pressed a button to start the game. The primary view showed what was in front of the agent depending on the direction of movement (Figure 3.2). This view had a restricted visual image of the environment. Therefore, a second view was added in the upper corner that had a top or map view of the intersection. This view showed an overview of the entire intersection and the movement of the agent and the robot. Since the different agents in a warehouse will be connected to a network it would also be possible to have such a map in a real environment as well.

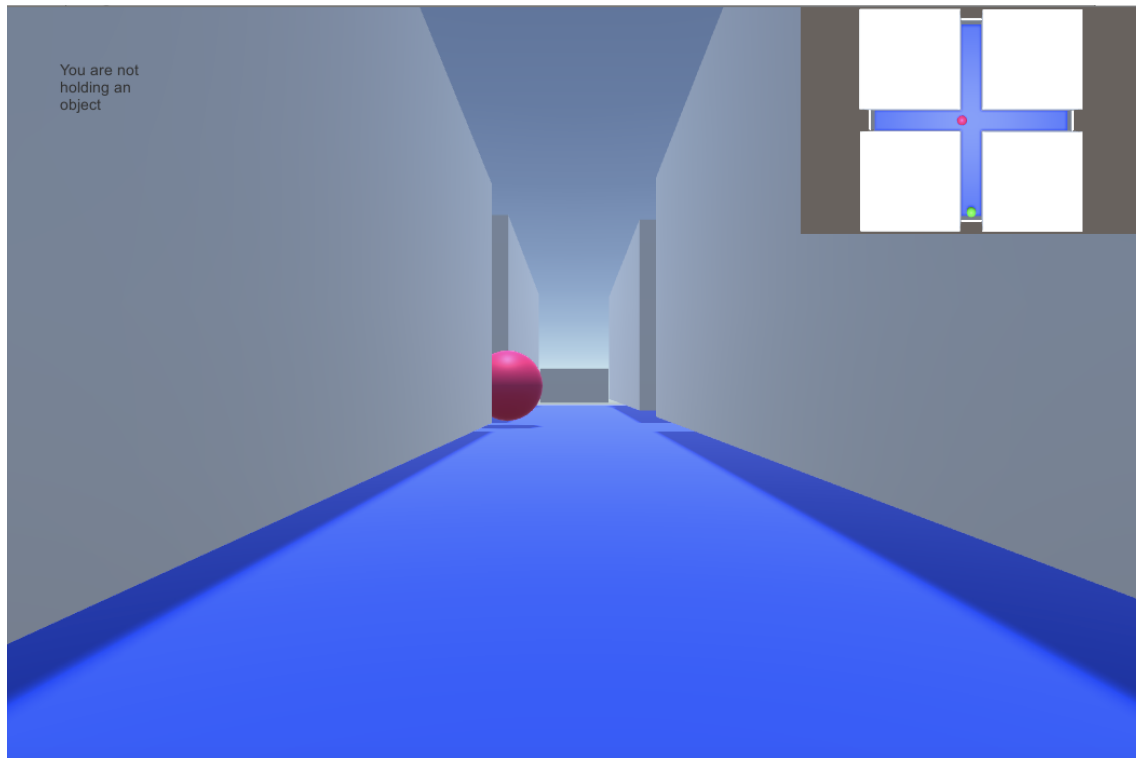


Figure 3.2: Game view for Human-Robot testing

### 3.4.2 Robot - Robot game view

In this scenario, the two views were not necessary since none of the agents were controlled by a human. For this implementation, the second view with a map view of the scene was used as the primary and only view (see Figure 3.3).

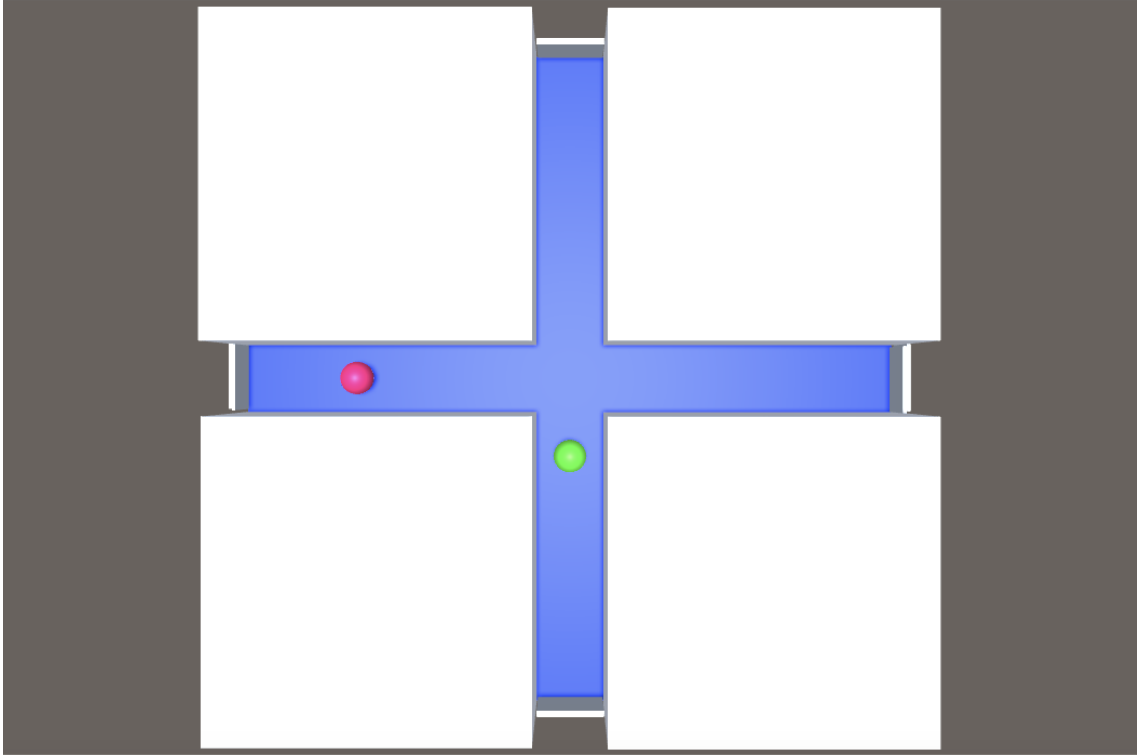


Figure 3.3: Game view for Robot-Robot testing

### 3.5 Human agent

The human agent was navigated by using the arrows on the keyboard. The Space-button was used as a break. We did not put any restrictions on how the human agent could move. This agent could use all four arrows (up, down, left and right) to move. The arrows affected the acceleration of the agent, which means that it continued to move with the same speed when the button was released. While pressing the button, the agent accelerated up to its maximum speed.

We used a green sphere to represent and distinguish the human agent. It also had a higher speed than the robot agent, to make sure that the test subject would have to make an active choice whether to work together with the robot or to finish the fastest.

### 3.6 Robot agent

The robot agents only moved either the x-axis or the y-axis (see Figure 3.4, the arrows show what direction the robots are moving), depending on what aisle they started in. If their holding-variable was "true", they moved towards the drop-off station, and if it was "false", they moved towards the pick-up station. The robot had a fixed speed set before the start of the simulation and would only move within its starting aisle and not cross over to the other aisle. The robot agent could also stop which would be decided by a protocol in the script.

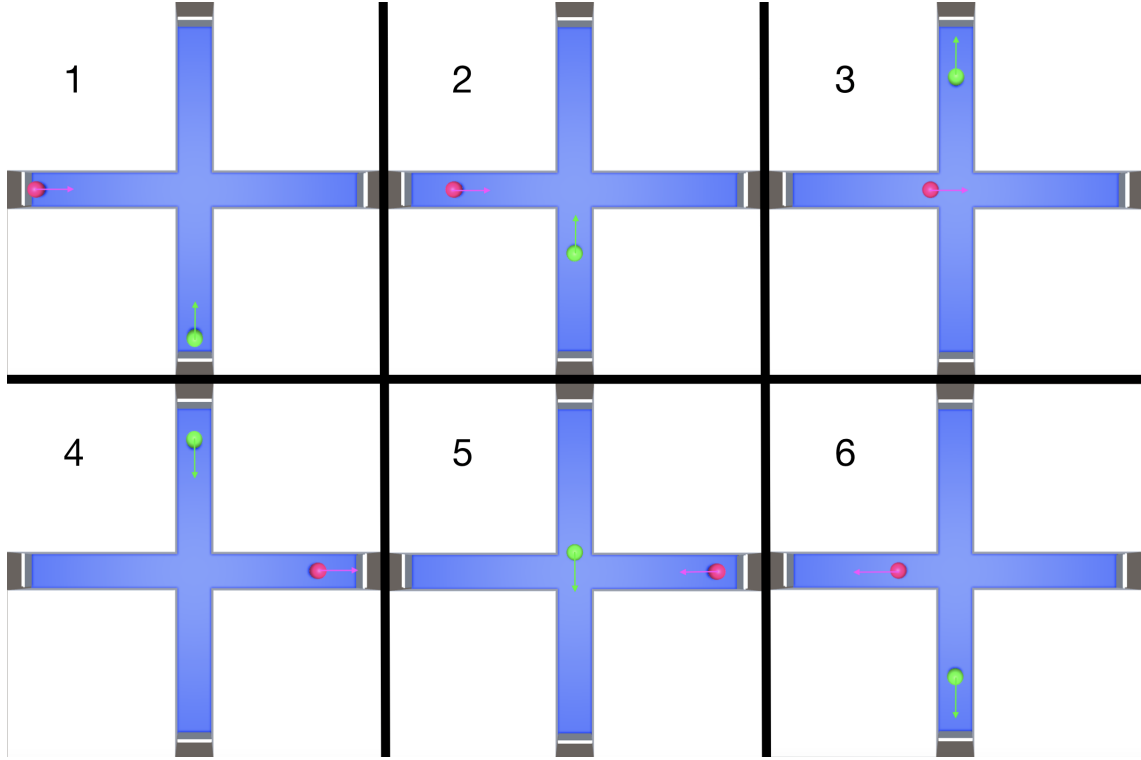


Figure 3.4: Overview of the robots movements in the environment

### 3.7 Using collision zone

We used collision zones in our implementations as described in Section 2.3. There was a collision zone in the intersection that consisted of two parts (see Figure 3.5). The yellow box where the robots checked if there were any other agents in the zone, this zone will be referred to as the checking zone and the red box where only one agent could operate at the same time, this zone will be referred to as the critical zone. When an agent entered the checking zone it updated a list of the agents that currently were located in the collision zones. Since we did not want the agent to stop in the critical zone the agent stopped checking the list when entering this zone. We also did not want other agents to be affected and stop after an agent has exited the critical zone but still was in the checking zone. The agent was therefore removed from the list when it exited the critical zone.

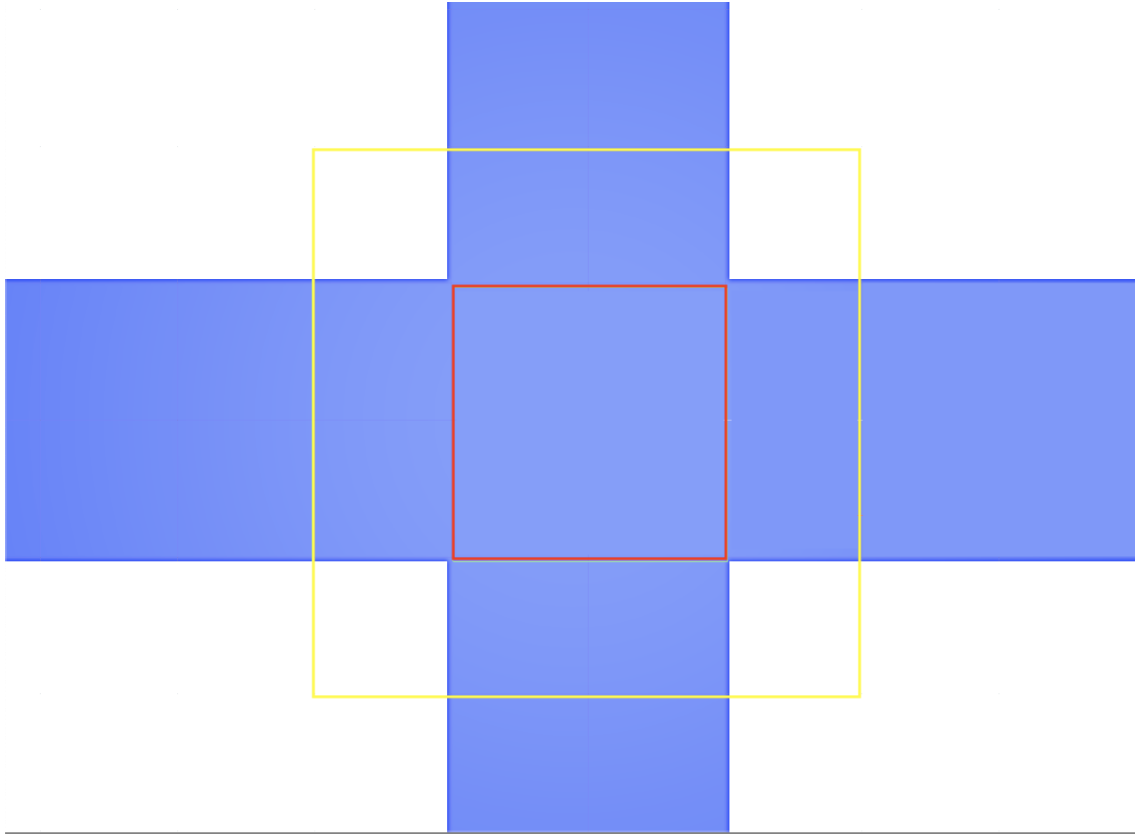


Figure 3.5: Collision zone

### 3.7.1 Human - Robot collision zone

In the environment with both the human agent and the robot agent, the human agent never reacted to the collision zone, while the robot agent always stopped in the checking zone if the human agent entered while it was still in the first zone. When the robot had entered the critical zone, it did not react to the human agent entering the collision zone, since this would make the robot stop in the middle of the intersection, creating a deadlock situation, where the robot was waiting for the human to exit the collision zone at the same time as it was blocking the path. The reason this worked was that the robot had already exited the intersecting path when the human reached it.

## 3.8 Hierarchical protocol

The robots in the simulations had a so-called hierarchy protocol. When they entered the first part of the collision zone the robots checked and compared the priority of the other, if any other agent is in the same zone. Both robots had the same priority from the start. If a robot had a lower priority than the other agent, it stopped before entering the second part of the collision zone. If the robots had the same amount of work left we chose to make the green robot stop. The agent that was navigated by a human always had a higher priority than the robots, meanwhile, the priority of the robots was updated depending on which one had most tasks left to complete.

## 3.9 Test

To receive data that we could use to analyze our problem statement, we performed tests in our environment. The following section will explain how we chose our test subjects and how we performed the tests in our different scenarios.

### 3.9.1 Test subjects

We used 27 subjects in our survey and they were drafted from our own personal network, most of them were students at KTH Royal Institute of Technology. This means that 135 tests were run in total. Since the subjects did not need any particular set of skills to perform the test, we did not have any specific requirements.

### 3.9.2 Human-Robot tests

During the Human-Robot testing we used fixed speeds for the two agents; the speed of 1 for the robot and the speed of 1.8 for the human. The test subjects received spoken instructions about the navigation system, how the five objects were picked up and dropped off, the presence of a robot agent with the same tasks and the fact that the timer would stop when both agents were finished. While performing the test the communication was kept to a minimum to allow the test subjects to explore for themselves. Technical help was only given when the test subject had misunderstood information about for example navigate. The data we collected during the tests was:

- Date and time of the test
- Completing time after every run
- General comments

The comments could, for example, be if there occurred any errors during the tests or the test subjects approach to solving the tasks. The data was stored in an Excel-sheet on a password protected computer.

### 3.9.3 Robot-Robot tests

During the Robot-Robot testing, we tried different speeds on the different robots to see how it affected the total time. We started with both robots having the same speed of 1 and repeated this scenario ten times. After that, we increased the speed of the second robot with 0.2. Ten tests were made with each combination of the first robot having the speed of 1 and the second robot having the speed of 1 through 1.8. We then set the speed to 1 on the second robot and increased the speed of the first robot. 90 tests were made in total.

## 3.10 Analyzing data

Once we had collected all the data we compiled them into graphs to give a clear presentation of the results. We performed different comparisons considering speed, which attempt it was and what kind of approach the test subject had towards the robot agent. The test subject was seen as cooperative if an active choice of waiting for the robot to cross the intersection before self crossing or not was made. We also created graphs which compared the different result from the Human-Robot tests and the Robot-Robot tests.



## Chapter 4

# Results

In this chapter, the results will be presented. The result will be presented in times for each run with the following format: mm:ss,00. Each test has been timed from that the start button is pressed till Unity automatically stops the timer when the test has been completed.

### 4.1 Robot-Robot

The first runs were the tests with two automatic robot agents. In these tests, each simulation was started with predetermined speeds on each robot.

#### 4.1.1 Result different speed

The Robot-Robot tests consisted of ten tests for each combination of the speed of the two robot agents. The tests were run ten times due to each test giving a slight difference in time at each run. In Figure 4.1 the letter P stands for the pink robot agent and G for the green robot agent. The following number shows the speed of each agent for that specific test. In other words P1:G1 means the speed of 1 for both the pink and the green robot agents. The speeds tested where both robots with the speed of 1. Then having one robot keep the speed of one while the other was changed to 1.2, 1.4, 1.6 and 1.8. This was then done again but swapping the robot that changed speed with the one that had a fixed speed of 1. This ended in 9 combinations of speeds tested.

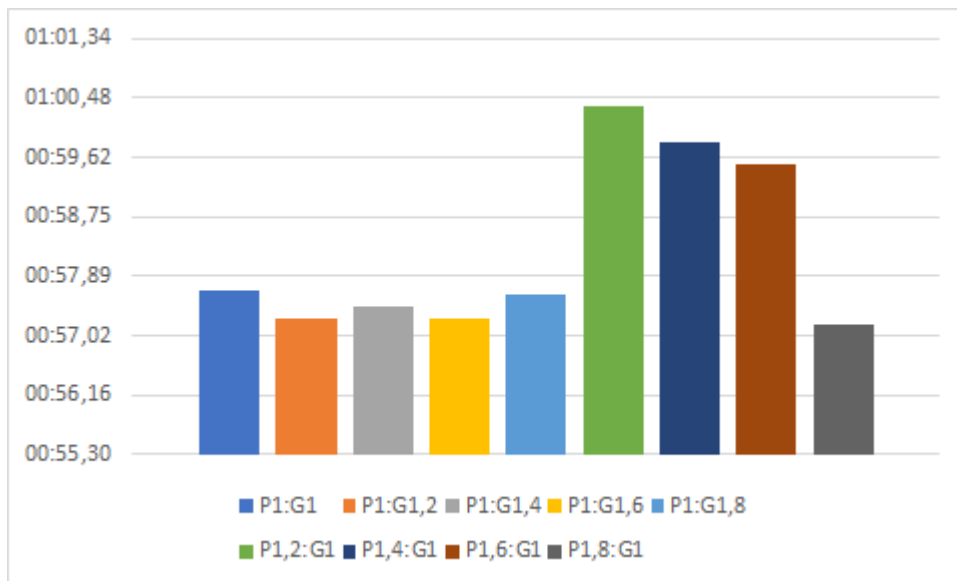


Figure 4.1: Average time depending on speed

Figure 4.2 represents the results and in the same order as Figure 4.1 although also with the standard deviation for each pair of speeds.

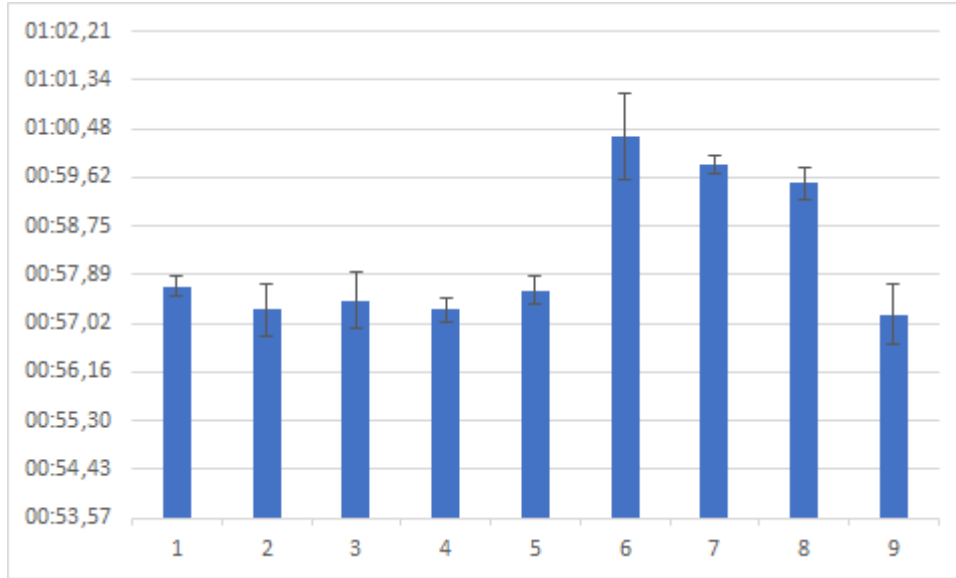


Figure 4.2: Average time depending on speed with standard deviation

## 4.2 Human-Robot

The next runs were the tests with one automatic robot agents and one human-navigated agent. In the following section, we will present the results from these tests. The results are from 27 tests subject with 5 tests each.

### 4.2.1 Test 1 through 5

The average time for the first attempts in the Human-Robot test was 01:23,36 (see Figure 4.3). The high average time was because the test subject was learning how to navigate the robot and getting used to the environment. Also seen in the first test is the larger range on the standard deviation showing a wider split between the test subjects highest and lowest time. The average time for the second attempts was 01:05,93. The standard deviation for the second test almost decreased to half the length from the previous attempts. The average time for the third attempts was 01:05,63, with another small decrease in the length of the standard deviation. The average time for the fourth attempts was 01:02,11. In this fourth test, the standard deviation increases slightly. Lastly, the average time for the fifth attempts was 01:04,08. with a standard deviation very similar to the fourth test.

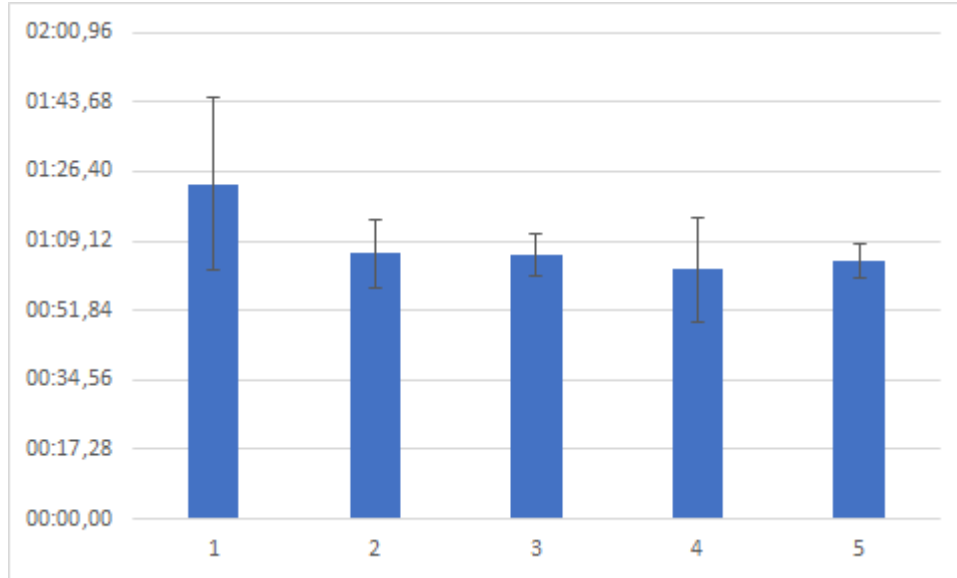


Figure 4.3: Average time test 1 through 5

#### 4.2.2 Test cooperative 1 through 5

We noticed that the test subjects had two different approaches toward the robot; either they cooperated with the robot or they did not. We determined this by observing and asking the test subject afterward. This is a graph of when the test subject cooperated with the robot Figure 4.4. The average time for the first attempts was 01:13,63. The average time for the second attempts was 01:04,94. The average time for the third attempts was 01:04,43. The average time for the fourth attempts was 00:57,94. Lastly, the average time for the fifth attempts was 01:01,52. The pattern for the standard deviation in these tests is very similar to the one described in previous section 4.2.1. A rather large spread for the first test and then reducing for test 2 and 3, spreading again for test 4 only to decrease for test 5.

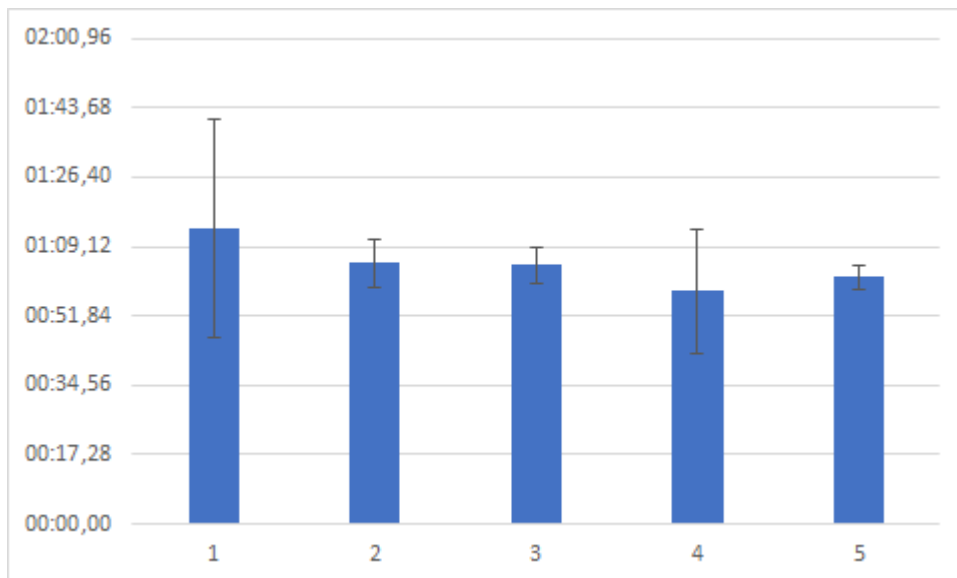


Figure 4.4: Average time cooperative test 1 through 5

#### 4.2.3 Test non-cooperative 1 through 5

The average times for the non-cooperative test subjects are shown in Figure 4.5. The average time for the first attempts was 01:31,85. The average time for the second attempts was 01:07,37. The

average time for the third attempts was 01:07,37. The average time for the fourth attempts was 01:08,17. Lastly, the average time for the fifth attempts was 01:07,80. The pattern for the standard deviation takes a different path in these results. The spread starts on the first test as the largest one and then decreases slightly for each new test and has the smallest spread for test 5.

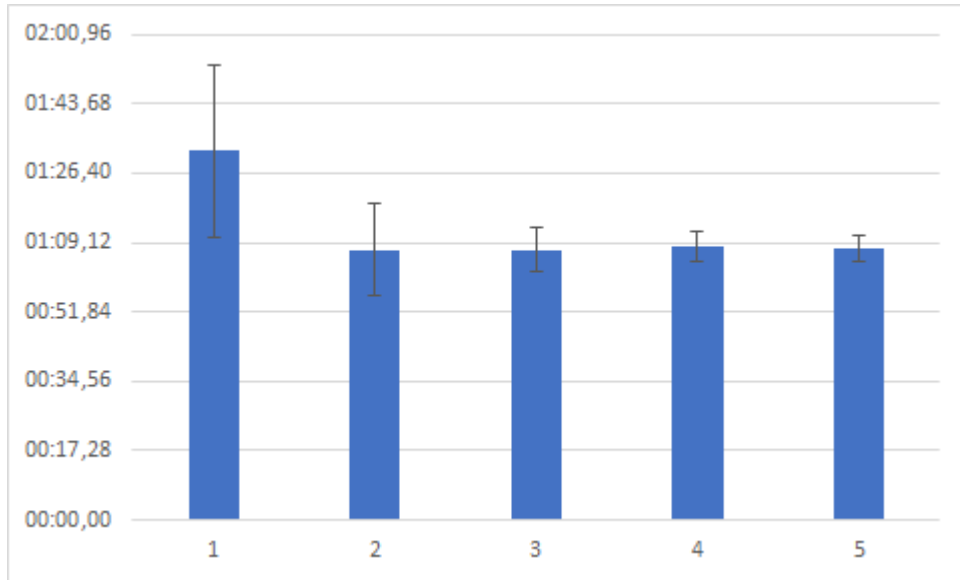


Figure 4.5: Average time non-cooperative test 1 through 5

#### 4.2.4 Average depending on attitude towards the robot

The average total time for the test subject that cooperated with the robot versus those that did not are presented in Figure 4.6. The average total time for those that cooperated is presented in bar 1 and was 01:04,49. The average total time for those that did not cooperate is presented in bar 2 and was 01:12,51. The standard deviation in both cases is almost identical.

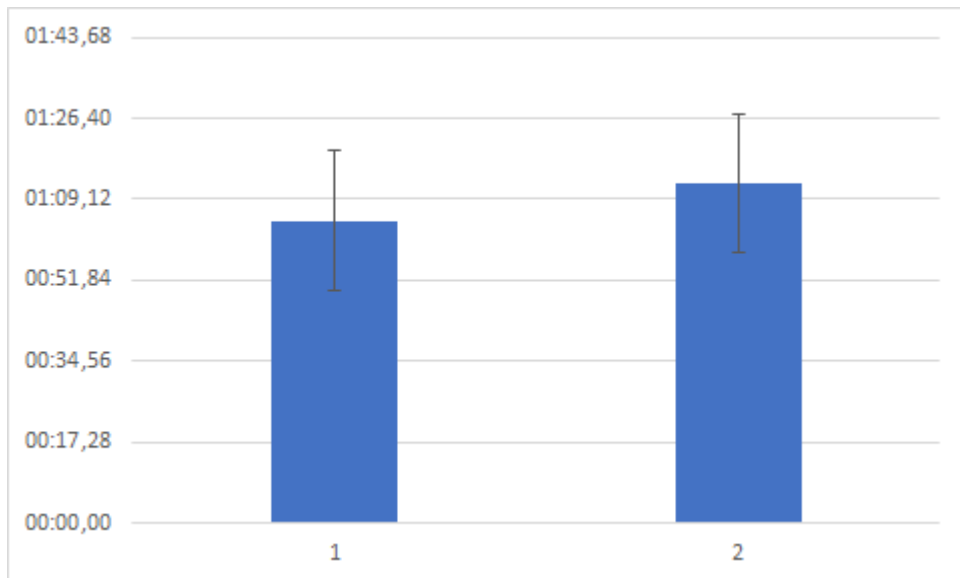


Figure 4.6: Average time depending on attitude towards robot

### 4.3 Robot-Robot vs. Human-Robot

In the following sections, we will present the difference between the Robot-Robot results and the Human-Robot results and compare them with each other.

### 4.3.1 Average and 5th test

In Figure 4.7 we present the average results from the Robot-Robot tests, the Human-Robot tests and the average result from the 5th Human-Robot test. The average time for all the Robot-Robot tests was 00:58,36. This average includes all the tests non-dependent of what different speeds the robot agents had. The different speeds varied from 1 to 1.8. The average time for all the Human-Robot tests was 01:08,22. During all these tests the robot agent had a speed of 1 and the human agent had a speed of 1.8. The average time for the 5th Human-Robot tests was 01:04,08. During all these tests the robot agent had a speed of 1 and the human agent had a speed of 1.8. The 5th test was the last one, and also when the test subject was most comfortable with the tasks and the environment.

The difference between the highest and the lowest result is approximately 10 seconds. Also, the standard deviation has a difference of over 10 seconds.

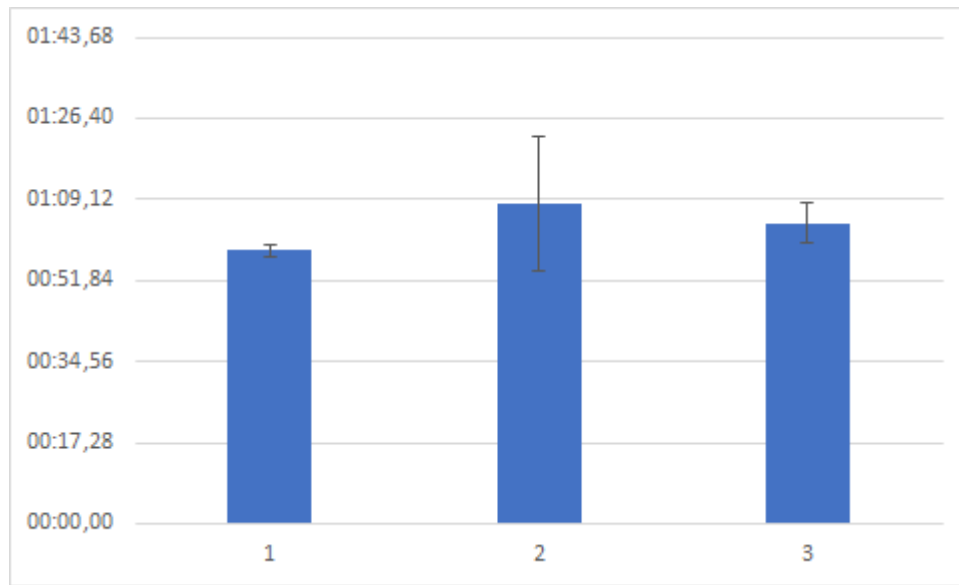


Figure 4.7: Average time Robot-Robot vs. all Human-Robot vs. 5th Human-Robot

### 4.3.2 Same speed

In Figure 4.8 the average time of Robot-Robot selected was only the ten tests with the pink agent with the speed of one and the green robot with a speed of 1.8 to represent the same conditions as the Human-robot tests. The average time for the Robot-Robot tests with these restrictions was 00:57,37. The Human-Robot average time was still the same as above, 01:08,22. The standard deviation in the Robot-Robot case is less than a second and the Human-Robot case is approximately 14 seconds.

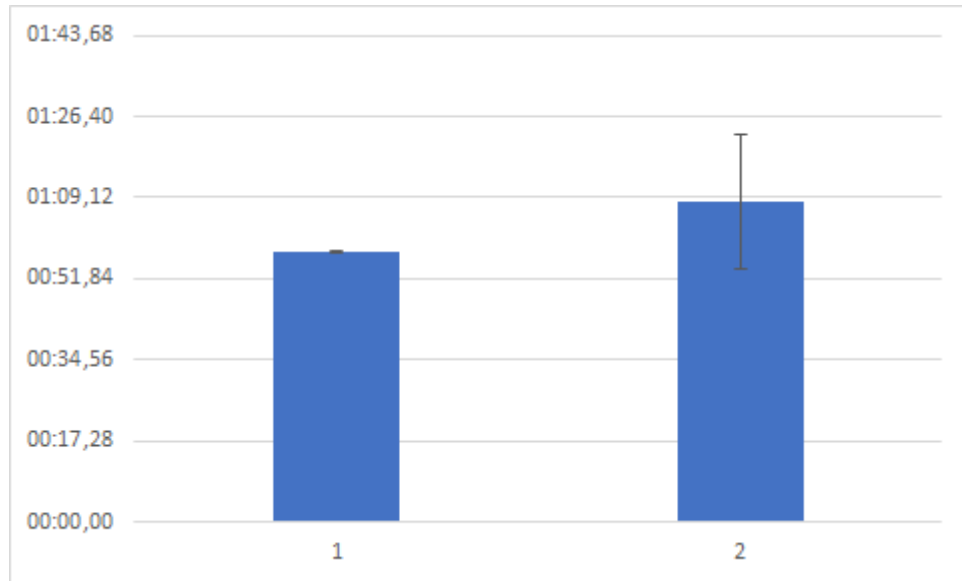


Figure 4.8: Average time Robot-Robot vs. Human-Robot with the same speed

### 4.3.3 Cooperative vs. Non-Cooperative

Figure 4.9 presents the total average time for the Human-Robot tests where the test subject cooperated with the robot, the total average time where the test subject did not cooperate with the robot and the total average time for the Robot-Robot tests. The total average time for the Robot-Robot tests is presented in bar 1 and was 00:58,36, the total average time for the Human-Robot tests with cooperation is presented in bar 2 and was 01:04,49 and the total average time for the Human-Robot tests without cooperation is presented in bar 3 and was 01:12,51.

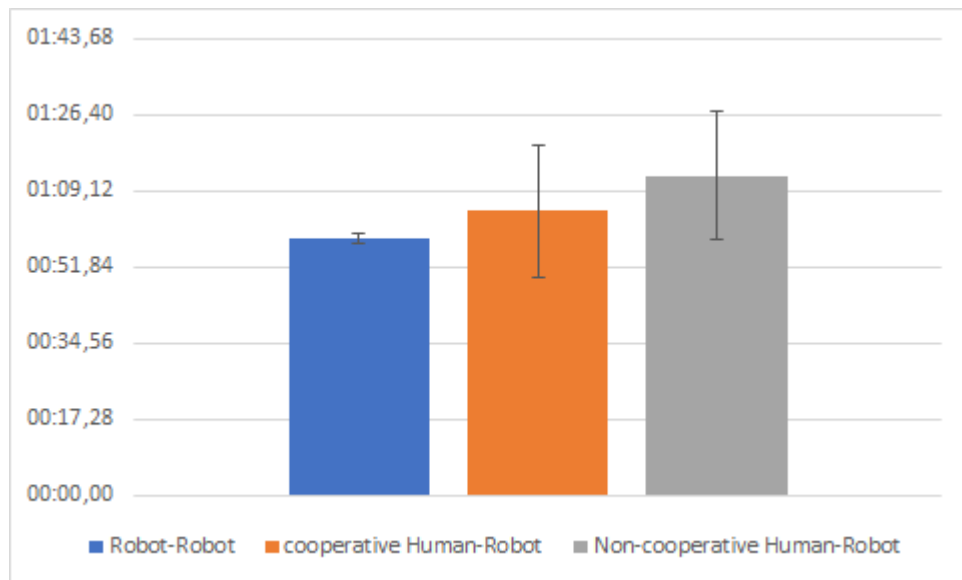


Figure 4.9: Cooperative vs. Non-Cooperative time

# Chapter 5

## Discussion

### 5.1 Robot-Robot

This section explains and discusses the results from both agents were robot-navigated.

#### 5.1.1 Difference in Robot-Robot tests

The Robot-Robot tests resulted in different times for the ten tests run under the same conditions. In some cases these differences were small but in other cases these differences were of a larger range. The cause of this difference is most likely because of how Unity runs on the test system. When the tests were done the computer did not have all of its computing power reserved specifically for only Unity to use. This means that during the runs the computer could simultaneously be using computing power on other actions and this could affect the times of the Unity runs. The average of these differences can be seen in Figure 4.2 This is the reason why not just one test for each condition was done but instead several and the average used in the graphs. The different speeds of the two agents also affected the result. The biggest difference was however not when the speed of the green agent was changed but when the speed of the pink one was changed. As seen in Figure 4.1 all the times with the pink agent with a fixed speed at 1 has a lower average time of completion than when the green agent had a fixed speed at one. The reason for this is because of how the priority protocol was designed. In the case of a tie at the intersection between the pink and the green robot, the pink robot always got priority to cross the intersection. In the cases where the green robot had a fixed speed of 1 and also might have to stop for the pink robot, this will have affected the time for the tasks to be completed by both robots.

### 5.2 Human-Robot

This section explains and discusses results about the tests where one agent was navigated by a human being and the other agent was robot-navigated.

#### 5.2.1 Five tests for Human-Robot

The Human-Robot tests were conducted five times with each test subject. In Figure 4.3 the average time for the first tests are shown to be slightly higher than the four following tests. The first test can be seen as an example of a human agent getting used to working in the same area as a robot. After the human agent has been accustomed to the workspace the average time becomes a bit lower and stays very close to each other even if more tests are done.

#### 5.2.2 Difference between cooperative and non-cooperative human test subjects

We noticed during the tests that our test subjects had different approaches towards the robot-navigated agent, which was not something we anticipated, and since it affected the results we decided to collect that data as well. Figure 4.4 shows the average times for the human test subjects that were clearly trying to get the best time possible by working together with the robot

during the tests. These subjects realized that if you made the robot stop and let you pass, the time for the work to be finished would be higher. The figure, therefore, has the highest time at the first test and the following tests vary depending on how well they managed to work with the robot. Figure 4.5 shows the average time for the human test subjects that did not take the robot agent into account when fulfilling their tasks. The figure has the first test of higher averages but the four following average times are very similar to each other. The four last non-cooperative tests had an average time 5-10 seconds slower than the last four cooperative tests. This would be due to the fact that the timer was stopped when both agents had finished their tasks. If the human agent made the robot stop this would directly make the result higher than if stopping the robot was avoided. As seen in Figure 4.6 the difference in time consumed between the two attitudes toward the robot agent is almost 8 seconds. Even though the result showed that having only robots crossing this kind of intersection is more time efficient, the difference between the cooperating and non-cooperating Human-Robot result is quite large, and therefore it could be interesting to research how much it is possible to improve the Human-Robot result by studying the human approach.

### 5.3 Robot-Robot vs Human-Robot

The average time for the Robot-Robot tests was in every case lower than the average time for Human-Robot tests, which means that our results showed that in our simulated environment, robots are more time efficient. The size of the difference changed depending on what Human-Robot tests were picked to compare with. The most difference was found between the Robot-Robot average time and the non-cooperative Human-Robot average times. The reason the Robot-Robot tests had a lower average was because of the robots being able to work together in a different way than the human agent could. The times for the Robot-Robot tests were almost always under a minute. To get similar times with the human agent the test subject had to actively avoid making the robot stop but also being able to pass just behind the robot in the last crossing of the intersection to then stop the timer under a minute. A number of human agents managed to get a time similar to the times of robot agents but this was not a consecutive result which therefore makes the average slightly higher in the end.

### 5.4 Our influence during tests

During the tests, the authors were present and sat next to the test subjects to make sure that everything worked smoothly. This could affect how the test subject acted and what approach they had towards the robot. Although since the influence was kept to a minimum the affect this had was not taken into account in the results.

### 5.5 Errors

There was a minor possibility for the human agent to collide with the robot agent. If the human agent would just slightly touch the robot agent it would not affect the time or the robot considerably. However, if the human agent had a high speed and managed to get a certain timing this could result in the robot agent ending up in the incorrect aisle, which meant that it could not complete the tasks. In the few tests that this occurred, that attempt was terminated and restarted, without counting it to the average time. The cause of this error is most likely because of the implementation of the protocols. In section 3.7.1 it is mentioned that in the case of the robot already being in the critical zone when the human controlled robot entered the checking zone nothing would happen. In this case, the robot should have the time to exit the zone and the intersection before the human-navigated robot entered. As seen in some cases this did not happen as anticipated. In some of the cases, the speed of the human-navigated robot made it possible to enter the critical zone and the intersection before the robot had the time to exit. Since this was not an expected error but one that appeared during the runs but also only in certain extreme cases it seemed acceptable to only be aware of the error but still use the results obtained as reliable. This occurrence happened seven times in a total of 135 tests.



## 5.6 Ethics and GDPR

When collecting the data from our test subjects we had to discuss ethics and GDPR (General Data Protection Regulation). Our test subjects were invited to an event where they signed up for a specific time slot. Our conclusion is that since all the data was anonymous and every person actively signed up for a time slot, our data collection is in compliance with GDPR.

## 5.7 Limitation

We could not do the tests with physical robots since we did not have access to any, therefore the simulated approach was the second best investigative option. There is always a difference between simulated and real environments, which is why it is hard to determine how much our results mirror reality. Another limitation was the small number of test subjects, which means that if one participant misunderstood the task and got a very high test-time it would have a high impact on the total average time. However our results still give an indication on what the results in the real world could be, and using a simulated environment is a much more cost efficient way of testing.

## 5.8 Future research

A few suggestions for how to continue this study in future researches are:

- Recreate the same tests but with physical robots instead of simulated.
- Add more robots and intersections to the environment.
- Use more complex and realistic warehouse tasks.
- Focus more on the human approach and how to affect it to give a more time efficient result.

## Chapter 6

# Conclusion

The use of robotics in warehouses are getting more and more common, but many warehouses are using restricted areas where only robots are allowed to operate. In environments where both human beings and robots are working together, this creates a need to have extra room, which is not always an easy problem to solve. Our question was if this was more time efficient, even if it was not space efficient.

We aimed to investigate this question by creating two different simulated environments with two agents that were supposed to cross an intersection to model picking up and leaving objects. One simulation had a human-navigated robot working alongside a robot-navigated agent, the other had two robot-navigated agents. In both situations, the robot-navigated agents had a hierarchy protocol that helped them avoid collisions. We then measured the time it took for both agents to complete their tasks and compared the result with the other situation. The results showed, as expected, that the robot-navigated agents were more time efficient, but also that it was possible for the human-navigated agents to succeed with their tasks on an almost as good time as the robots if they cooperated. This shows that in those cases where human interact with robots, it is possible to affect the time by changing their approach. To investigate this subject more thoroughly one could recreate the test with physical robots and a more thorough analysis of the human approach and what promotes collaboration with the robot.

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