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Can cheap robotic vacuum cleaners be made more efficient?

A computer simulation of a smarter robotic vacuum cleaner

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Abstract

Robotic vacuum cleaners are popular domestic robots that clean floors without human intervention. The purpose of this report is to study how cheap robotic vacuum cleaners' navigation pattern can be improved. This is achieved by simulating two models of robotic vacuum cleaners, one "simple" and one "smart", both relying on the knowledge that cheap sensors can provide about the surrounding environment. As the results show how the smart robot is better than the simple robot in all simulations in terms of floor coverage, the results are considered successful. The fact that the simulations are simplified versions of real-life robotic vacuum cleaners is discussed, and future work could consider examining more realistic simulations or experiment on real-life robotic vacuum cleaners.

Sammanfattning

Robotdammsugare är populära hushållsrobotar som städar golv utan människors inblandning. Syftet med den här rapporten är att undersöka hur billiga robotdammsugares navigeringsmönster kan förbättras. Detta görs genom att simulera två modeller av robotdammsugare, en “simpel” och en “smart”, där båda förlitar sig på information som billiga sensorer kan ge om omgivningen. Resultaten anses vara lyckade då de visar hur den smarta roboten presterar bättre än den simpla roboten i alla simulationer. Faktumet att simulationerna är simplifierade versioner av verkliga robotdammsugare diskuteras och framtida forskning kan undersöka mer realistiska simulationer eller experimentera med riktiga robotdammsugare.

Contents

Chapter 1

Introduction

In recent years we have been witnessing how robots are rapidly being integrated into our lives, altering modern life as we know it. Robotic vacuum cleaners such as iRobot's Roomba, Neato's Botvac and Eufy's RoboVac are just a few examples of robots that are used in domestic environments. Robotic vacuum cleaners' purpose is to clean rooms automatically, with little to no human guidance. To make this possible, these robots move with the help of navigation systems consisting of mechanics, electronics and sensors, amongst other things. The cheaper robotic vacuum cleaner models tend to rely on haptic sensors and infrared light, while the expensive and more advanced models include complex navigation systems using cameras or pulsing laser light. The simpler models' maneuvers are based on certain movement rules, resulting in a random navigation pattern [8]. The more advanced robotic vacuum cleaners are often more efficient than the simpler models because of their more sophisticated navigation patterns and often tops the lists of reviews [3] [14]. However, they are also more expensive, costing up to around $1000 [4].

1.1 Purpose

The price of more advanced models makes it an impossible investment for many households. The purpose of this report is therefore to study how cheap robotic vacuum cleaners' navigation systems perform in comparison to more advanced models and how the cheap models' navigation systems can be improved.

1.2 Problem statement

The main aim of this study is to investigate if it is possible to increase the level of efficiency of a robotic vacuum cleaners' navigation system using the technology available in cheaper models. More specifically, what changes in the cheaper models' navigation system can be made to make it more efficient?

1.3 Scope and Approach

For this study two simplified computer simulations of robotic vacuum cleaners will be created to measure floor coverage. If successful, it would imply that there could be changes made to cheaper models of robotic vacuum cleaners in real-life to increase their level of efficiency.

Chapter 2

Background

In this section, the mechanics behind robotic vacuum cleaners in general will be described, followed by an in-depth description of specific robotic vacuum cleaner models mentioned in this report, as well as a description of different types of computer simulations.

2.1 Robotic vacuum cleaners

Robotic vacuum cleaners are the most popular robots in domestic environments since they first came to the market back in 2002. They are able to efficiently clean floors by themselves with the help of their navigation systems based on navigation theory, using real time path planning and obstacle avoidance theories originally developed in the field of mobile robots [16].

Whether the robotic vacuum cleaner consist of simple or more advanced technology they all have the same purpose: to clean floors in an efficient way. Therefore, all models of robotic vacuum cleaners will have to solve certain problems such as obstacle avoidance, floor coverage and time planning in order to travel back to its loading station before running out of battery. How well they perform at solving these problems, together with factors such as suction and noise levels, are what reviewers tend to look at when comparing different models of robotic vacuum cleaners.

2.1.1 iRobot's Roomba 605

iRobot's Roomba 605 is one of iRobot's cheapest robotic vacuum cleaners, costing about $200 as of 2018. Its navigation system consists of infrared sensors; cliff sensors and wall sensors. The cliff sensors consist of four infrared sensors which constantly sends out signals. If these signals do not immediately bounce back, the Roomba knows that it has moved too close to stairs and backs away, thus avoids falling down. The wall sensors let the Roomba follow walls closely without having to bump into them and it does so by sending out infrared signals in order to keep a certain distance to walls and objects [12].

It also has mechanical object sensors that tells the Roomba that a bumper has retracted and that an obstacle has been encountered. When the Roomba encounters an obstacle and gets stuck, it uses its bumper sensors and performs the sequential actions of reversing, rotating and moving forward until its path is clear [12].

After having cleaned the whole room or if it is almost out of battery, the Roomba can navigate itself back to its charging station. This is accomplished by the infrared receiver located on the front of the robot. The charger station emits infrared signals and the Roomba returns to it by following these signals [7].

The navigation pattern that the Roomba 605 uses consists of certain rules. Firstly, if the robot is moved to a dirty spot by a human, the robot moves in a spiral movement outwards until bumping into an obstacle. When reaching an obstacle or a wall, it changes to "wall-following" for a short time. After a certain distance, the robot turns at a random angle and continues going straight until it again bumps into an obstacle or changes into moving in an outward spiral [3].

2.1.2 iRobot's Roomba 980

iRobot's Roomba 980 is iRobot's most expensive robotic vacuum cleaner, costing up to $900 as of 2018. The navigation system in this model is based on VSLAM (Vision Simulation and Mapping). On the top of the Roomba a camera is mounted forward and up about 45 degrees. The use of VSLAM enables the robotic vacuum cleaner to dynamically build a map of its environment and the robots knowledge of its environment is constantly improved [2].

During scanning, the robot creates new visual landmarks. These landmarks consist of collections of unique features extracted from an image. The robot then links this landmark to its current position, the x and y and heading coordinates [11]. As this is done repeatedly throughout the room, new landmarks are created and when necessary the odometry is corrected.

The Roomba 980 can however not only rely on the use of VSLAM because it will find itself under furniture where creating new landmarks and connecting them to the rest of the map will be difficult. It can also emerge in places that has little to no visual features, making it difficult to create landmarks. In these cases, it has to rely solely on its wheel odometry.

The navigation pattern that the Roomba 980 uses is sophisticated, moving from side to side in the room, advancing as it bumps into either walls or obstacles. If it gets stuck it uses the same technique as the Roomba 605, performing sequential actions of reversing, rotating and moving forward until the path is clear [6].

2.1.3 Neato's Botvac

Neato's Botvac comes in different types of models, with prices ranging from $500 to $900 as of 2018, with navigation systems relying on LIDAR (Light Detection and Ranging). The turret on the top of the robots has a spinning laser emitter and detecting system called Revo LDS (Revolving Laser Distance Sensor). This fires up to 4,000 infrared laser pulses per second while rotating, providing a 360-degree field of view around the robot, watching for the reflection of each pulse. It then calculates the distance and angle of what the pulse reflected off of and the robotic vacuum cleaner is capable to calculate measurements for objects up to 5 meters away [1].

The Botvac uses laser distance sensors for their speed and accuracy. This is similar to the technology used by autonomous cars, but to keep the price down the Revo LDS used in these robotic vacuum cleaners are developed by Neato to only apply to the standards of indoor environments.

The LIDAR units are active sensors and because of the fact that they produce their own light, low light conditions have no effect on these types of sensors [9]. However, since the LDS cannot detect obstacles that are shorter than the robotic vacuum cleaner's own height, it also has other sensors for obstacle avoidance such as bumper sensors and cliff sensors [9].

2.2 Obstacle encountering and navigation systems

One of the biggest issue with robotic vacuum cleaners is their ability to avoid obstacles. Models that rely heavily on bumper sensors to navigate the existence and location of objects can both harm the environment and the robot itself. Both robots with IR sensors and robots with cameras also faces problems with obstacles. IR sensors are not always accurate enough to inform the robot of the correct positions of obstacles due to their narrow search range. Robots with cameras has problems related to when their cameras are not able to map the room, like mentioned previously [10].

When the robotic vacuum cleaners are not encountering objects, their mission is to sweep the floors, thoroughly vacuuming all of the reachable floor area. Different models of vacuum cleaners have different navigation patterns, but their movement across an environment tends to correlate to the robotic vacuum cleaners model, where models with simpler hardware and lower price, such as iRobot's Roomba 605, often have a more random movement pattern and models with more advanced hardware and higher price, such as iRobot's Roomba 980, most often have more coordinated movement patterns [13].

2.3 Simulation

There are multiple methods to study the behaviour of real-life situations. Mathematical analysis, real-life experiments, prototype analysis or simulating a system with the help of a computer are a few examples of methods. Computer simulations are often valuable for understanding real world processes because of the well-defined relationships that are necessary for trustworthy results [5] .

Creating real-life experiments or analysing a complex system mathematically is considered nearly impossible in many cases due to the problems involving many variables, many parameters and also variables that appear random [15].

The two main types of computer simulations are called discrete models and continuous models. Some problems only fit into one type of model whereas for some problems either type of model can be used. Continuous models are closer to reality, but it is often less complicated to use discrete models.

Discrete models are concerned with systems such as events and probability distribution, run many times to give probability predictions. In the discrete model, the systems state and parameters are discrete.

Continuous models make use of real numbers and differential equations. These models are used when the problems parameters change continuously and are often represented mathematically by difference equations describing the rate of change of variables over time.

Chapter 3

Initial considerations and hypotheses

The simulations are built to resemble robotic vacuum cleaners' performance. The goal with the simulations are to gather data on how a robotic vacuum cleaner's navigation system performs in an environment if the navigation pattern is either similar to the navigation pattern of the iRobot's Roomba 605 described in Chapter 2.1.1, referred to as the simple robotic vacuum cleaner, or a model with a further developed navigation pattern, similar to the one in the iRobot's Roomba 980 described in Chapter 2.1.2, referred to as the smart robotic vacuum cleaner. The simulation of the smart robotic vacuum cleaner will still only rely on cheap sensors.

3.1 Methodological considerations

For this study to fulfill its purpose there are methodological issues that has to be considered. Firstly, how will it be determined that one navigation pattern is better than another? Secondly, how will it be determined that the results are reliable?

To resolve these issues, there will be multiple environments to ensure that it does not favor one of the simulated navigation systems. To determine the performance of the navigation pattern there will be certain variables that will be compared, such as floor coverage and time span.

3.2 Implementation considerations

There will be eight types of environments that will be simulated, and we expect that they will consistently show that the same type of simulated navigation pattern performs better. The different environments will have different sizes and different number of obstacles.

The two different robotic vacuum cleaners that are simulated will have different motion planning algorithms and these will determine the movement of the robotic vacuum cleaner. The environments with obstacles will require more maneuvering for complete floor coverage.

3.3 Hypotheses

There will be two types of environments, rooms with obstacles and rooms without obstacles. Simulating these different environments with the two models of robotic vacuum cleaners, the expected result is that the smarter robotic vacuum cleaner will perform better than the simple robotic vacuum cleaner in rooms with no obstacles and in rooms with obstacles the smarter robotic vacuum cleaner will perform slightly better than the simple model.

Multiple simulations of the simple robotic vacuum cleaner with different environments compared to the same simulations of the smarter robotic vacuum cleaner should result in similar proportions in the simulations. By both making several simulations of the same environment and comparing them to several simulations in different environments, we expect to show that our hypotheses are correct and that the results are dependable.

Chapter 4

Method

The following chapter will describe the simulation type and how the environment and robotic vacuum cleaners were modelled. It will also describe how the different navigation systems function and thoroughly define their behavior.

Since there has only been few similar studies made, the simulation that was built is based on our assessment of what is reasonable during the time frame of this project. The final result will not be able to fully simulate real-life robotic vacuum cleaners but give an idea of simplified versions of them.

There are multiple occasions where the simulation is different from reality. When it comes to environments and objects, they can in reality exist in all shapes and sizes but in the simulation, there are restrictions to both shapes and sizes. For example, in the simulation all objects have rectangular shapes.

In order for the simulation to give reliable results, the robotic vacuum cleaners in the simulations assumes that the robot's coordinates are known exactly. In reality, this is not achievable due to the lack of exact wheel movement.

4.1 Simulation

Since the objective of this study was not to continuously track the simulation of the robot, but rather to gather data from consecutive events from the simulation, the type of simulation used was a discrete event simulation. One discrete event resembles one particular part of the environment being vacuumed, directly depending on the robotic vacuum cleaners position.

The two robots that were modelled were simulated in the same type of environment, with the same type of obstacles, and this ensured that the performance of the two robots navigation systems could be compared.

To fulfill the aim of this study, the two different models of robotic vacuum cleaners that were simulated have the same achievable knowledge of their surroundings. In the simulations, the robots only know their immediate environment, up to a short distance away from the robot itself, which replicates the knowledge that IR sensors gives robotic vacuum cleaners in real-life. Other factors that were kept the same between the two models of robotic vacuum cleaners were their size and shape.

4.1.1 Environment

The environment in the simulation consisted of a room with x and y coordinates connected to squares on the floor called tiles. Each tile could either be a tile with a dust particle, a tile with an object or a tile with neither dust nor object on, i.e. an already vacuumed tile.

The border tiles were made into object tiles, forming a wall around the room. Object tiles could then also be positioned on all tiles that were not wall tiles, and multiple object tiles put together could form various shaped obstacles.

While the robots move around in the environment and traverses the tiles with dust particles, the dust particles get vacuumed up. Each tile it moves over equals one step of the robot, whether or not it has already vacuumed that specific tile. If all the dust particles have been removed by the robot, the simulation ends.

4.1.2 Simple robotic vacuum cleaner

The first robotic vacuum cleaner that was modeled was a close replication of the Roomba 605 described in chapter 2.1.1, with a navigation pattern that is seemingly random. In the simulation, the movement pattern was broken down into certain functionalities and the robot was able to perform wall following, 360 degrees movement, as well as its ability to, after a restricted random number of steps, turn at a restricted random angle.

If the robot hits an object tile, it will use its wall following until it is at the edge of the obstacle and then continue outwards in the same direction until it hits another object tile. It can only detect obstacles that are within its reach, mimicking the behaviour in the real world with IR sensors.

4.1.3 Smart robotic vacuum cleaner

The second robotic vacuum cleaner that was modeled for the purpose of this study was a smarter version of the Roomba 605 described in chapter 2.1.1. It was intended to model how a robotic vacuum cleaner with the same kind of hardware found in the described robot could get improved performance, concerning floor coverage, when altering the navigation algorithm.

This model's navigation system relies on a movement from top to bottom of the room, vacuuming each row until moving on to the next column of the room. If the robot hits an object tile, it will simply regard it as a wall tile and turn to continue its movement.

The smarter navigation system memorizes the tiles that the robot has previously visited. If the robot passes a tile to the left that it has not yet vacuumed, it will turn left and continue forward until the tile to the left no longer is unvisited. Thereafter it will continue its sweeping movement from top to bottom.

Just as with the simple robotic vacuum cleaner, the smart robotic vacuum cleaner can only detect obstacles that are within its reach. Therefore, it does not know where obstacles are in the environment until a sensor has noticed it and the robot is able to map the room without any visual input.

4.2 Tools

The simulation was written using the programming language Java. The figures were made using excel. To support the development of the simulation, to simplify debugging and to demonstrate the navigation systems, a visual depiction of the simulation was implemented. Both Java Swing and Java Abstract Window Toolkit was imported for the visual representation of the simulation. Figure 1 and 2 shows how an ongoing simulation of the robots could look.

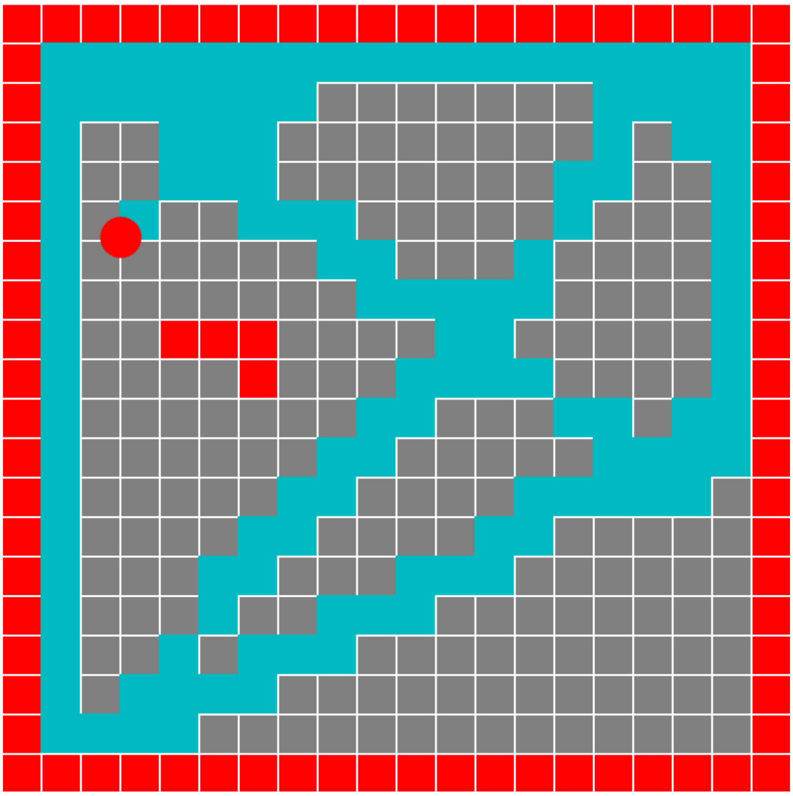

Figure 1. Screenshot of ongoing simulation of simple robotic vacuum cleaner. Red tiles are wall and object tiles, grey tiles are dust particles, blue tiles are vacuumed tiles and the red circle is the robotic vacuum cleaner.

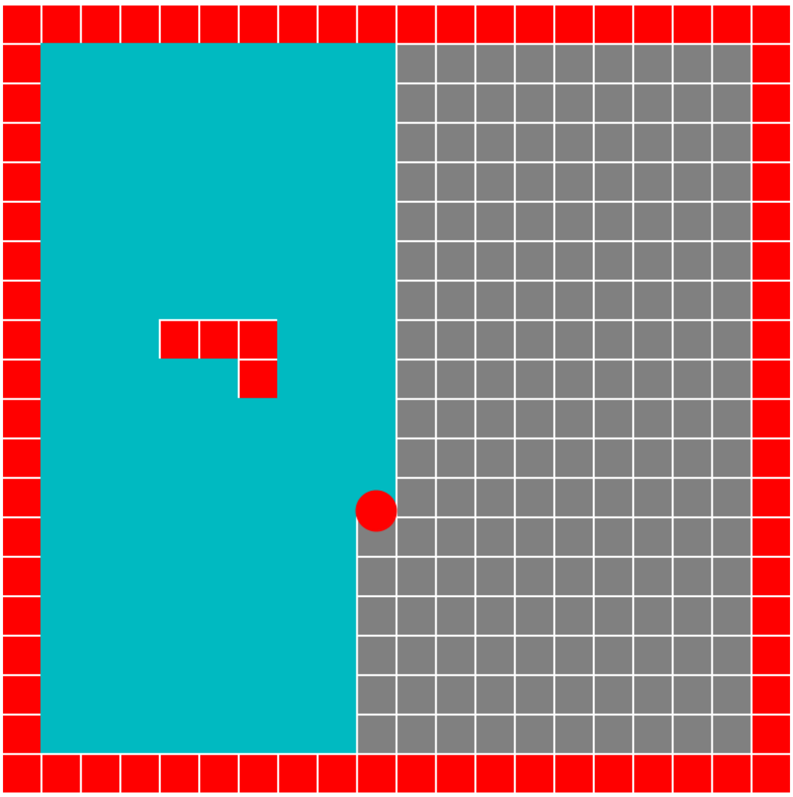

Figure 2. Screenshot of ongoing simulation of smart robotic vacuum cleaner. Red tiles are wall and object tiles, grey tiles are dust particles, blue tiles are vacuumed tiles and the red circle is the robotic vacuum cleaner.

Chapter 5

Results

This chapter describes the results retrieved from the simulations and is divided into two parts. The first part concerns the end results of the simulations of different rooms and the performance of the two different models of robotic vacuum cleaners. The second part of this chapter illustrates the process of cleaning different rooms for the different models of robotic vacuum cleaners.

5.1 Steps until cleaned room

For the simple robot, a total of 50 simulations per room where run, each simulation running until there were no dust particles left. The starting position for the robotic vacuum cleaner was in the upper hand left corner for each simulation. Because of the fact that the smart robot did not rely on any random factor, it was only run once.

Room	Smart robot, number of steps until cleaned	Simple robot, number of steps until cleaned, mean	Simple robot, sample standard deviation
10x10 No obstacle	64	350	108,4
10x10 One small obstacle	64	437	155,7
10x10 One big obstacle	70	575	298,2
20x20 No obstacle	324	2833	661,6
20x20 One small obstacle	324	3153	681,6
20x20 One big obstacle	340	3607	1030,6
20x20 One small obstacle, one big obstacle	368	4034	1256,9
20x20 Three small obstacles	324	4342	1851,6

Figure 3

For every room a mean for the simple robotic vacuum cleaner was calculated. Figure 3 shows the performance of the simple robotic vacuum cleaner next to the performance of the smart robotic vacuum cleaner.

5.2 Cleaning process

The following graphs illustrates the cleaning process of the 8 different rooms for the different models of robotic vacuum cleaners, showing the number of dust particles left for each step taken by the two different models of robotic vacuum cleaners. The layouts of the different rooms can be found in Appendix A.

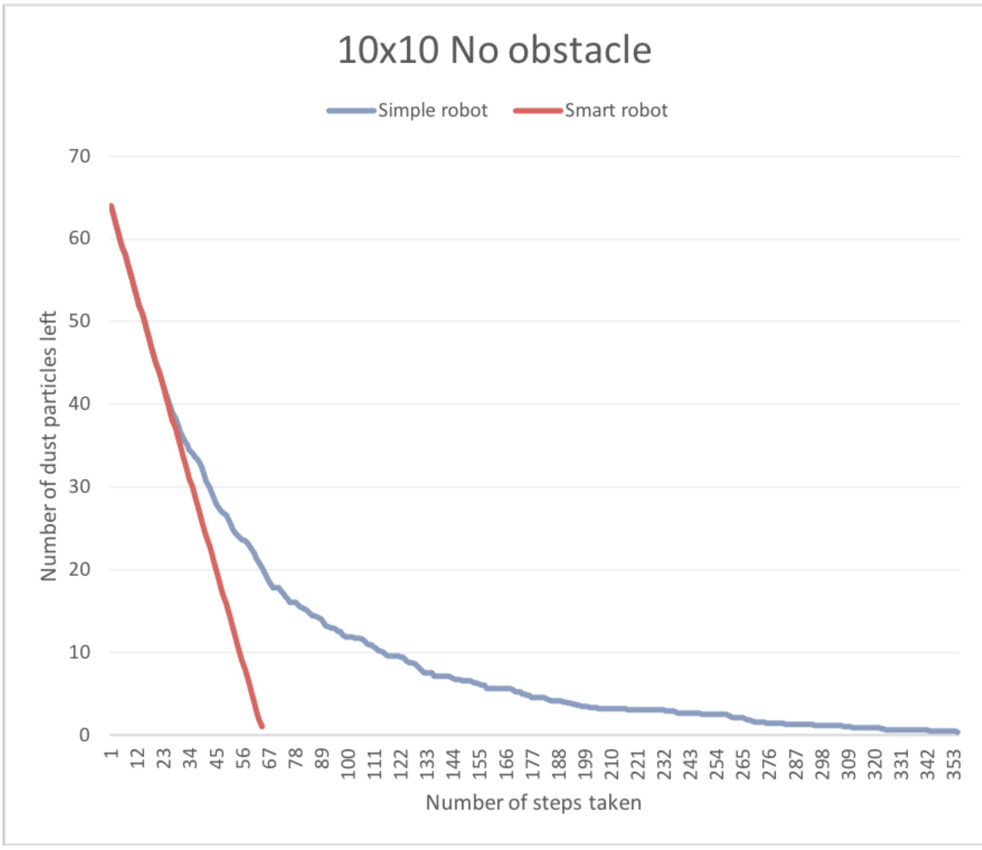

Figure 4. Room 10x10 with no obstacle.

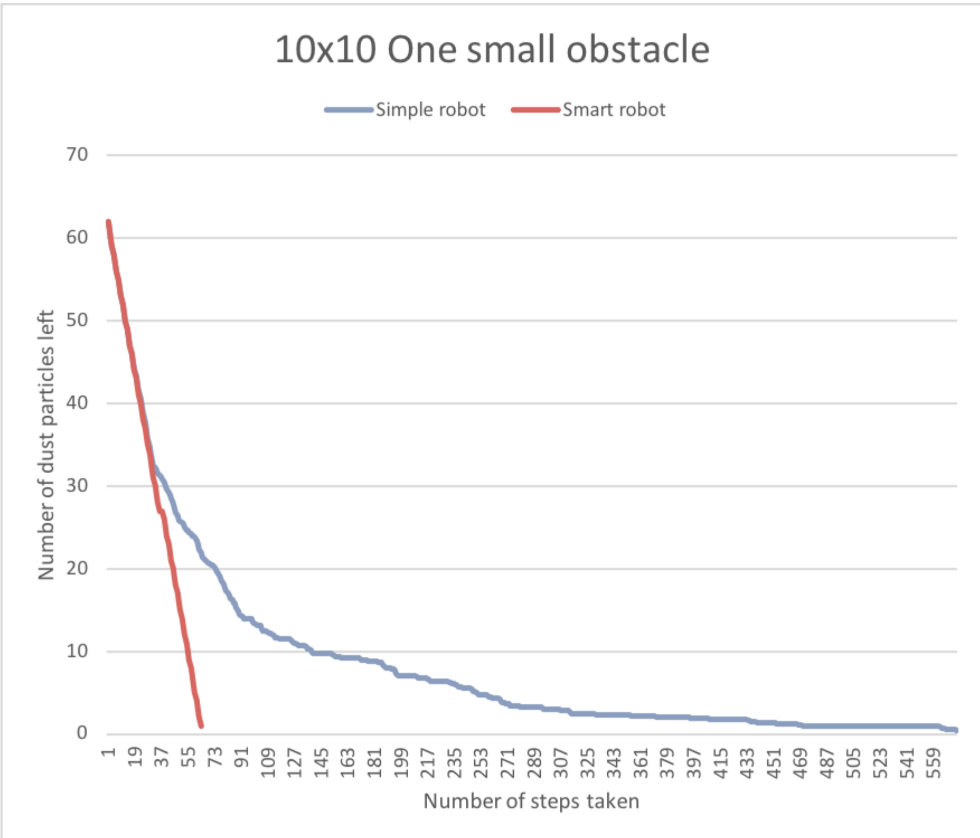

Figure 5. Room 10x10 with one small obstacle.

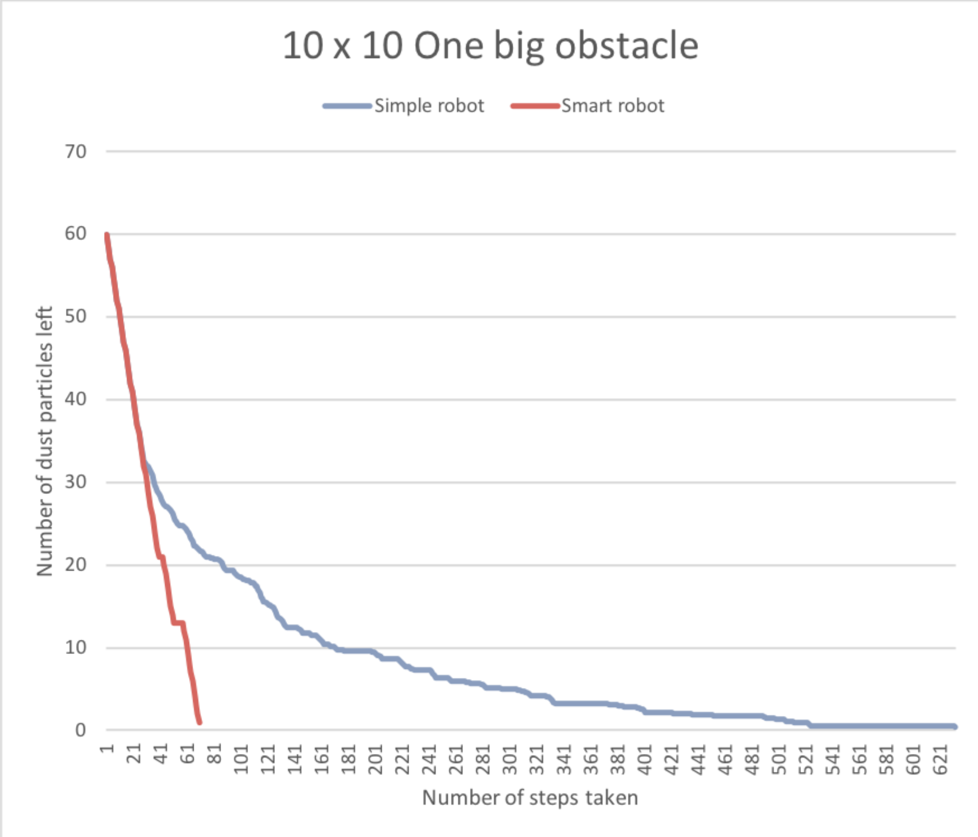

Figure 6. Room 10x10 with one big obstacle.

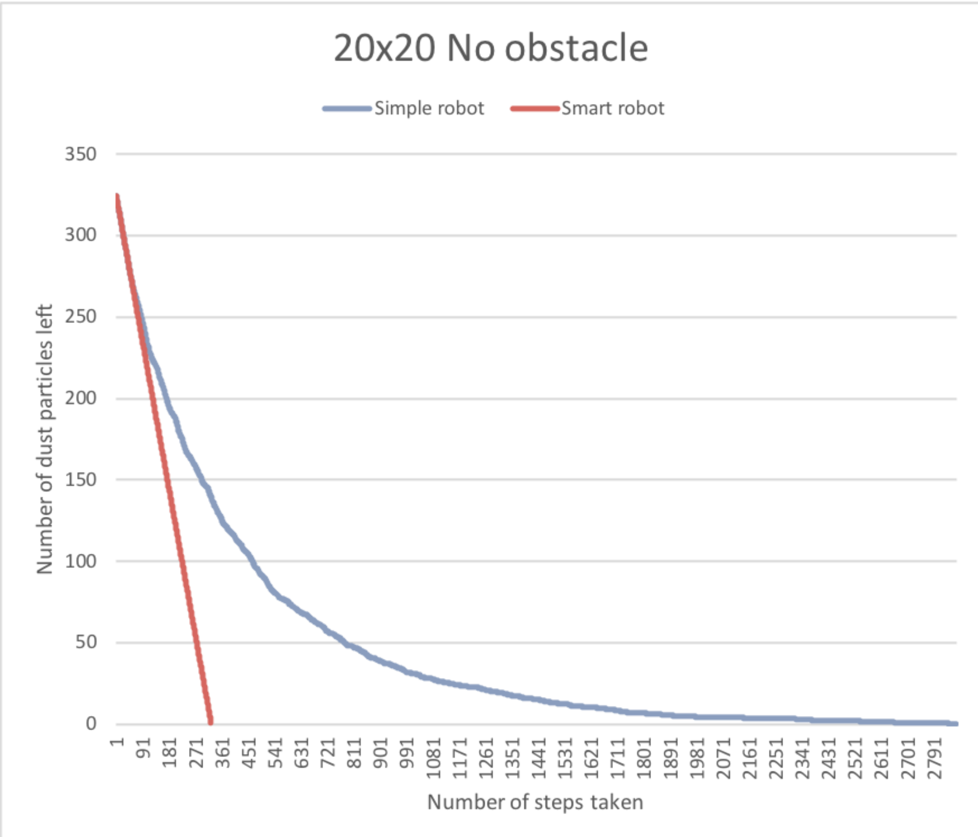

Figure 7. Room 20x20 with no obstacle.

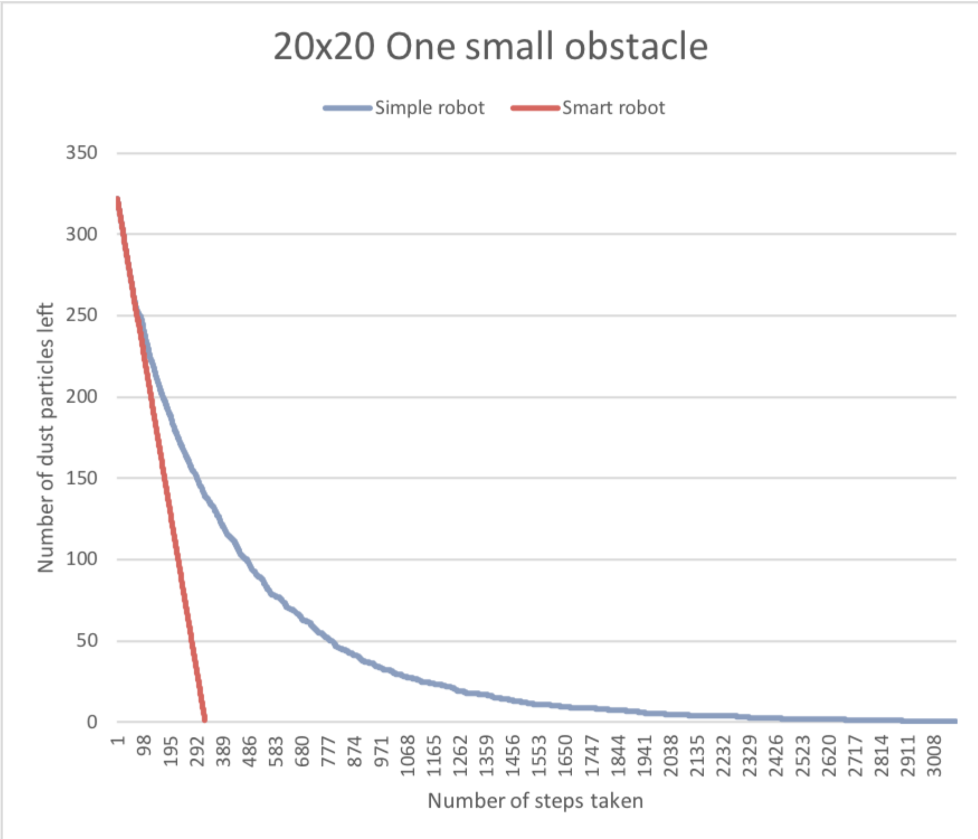

Figure 8. Room 20x20 with one small obstacle.

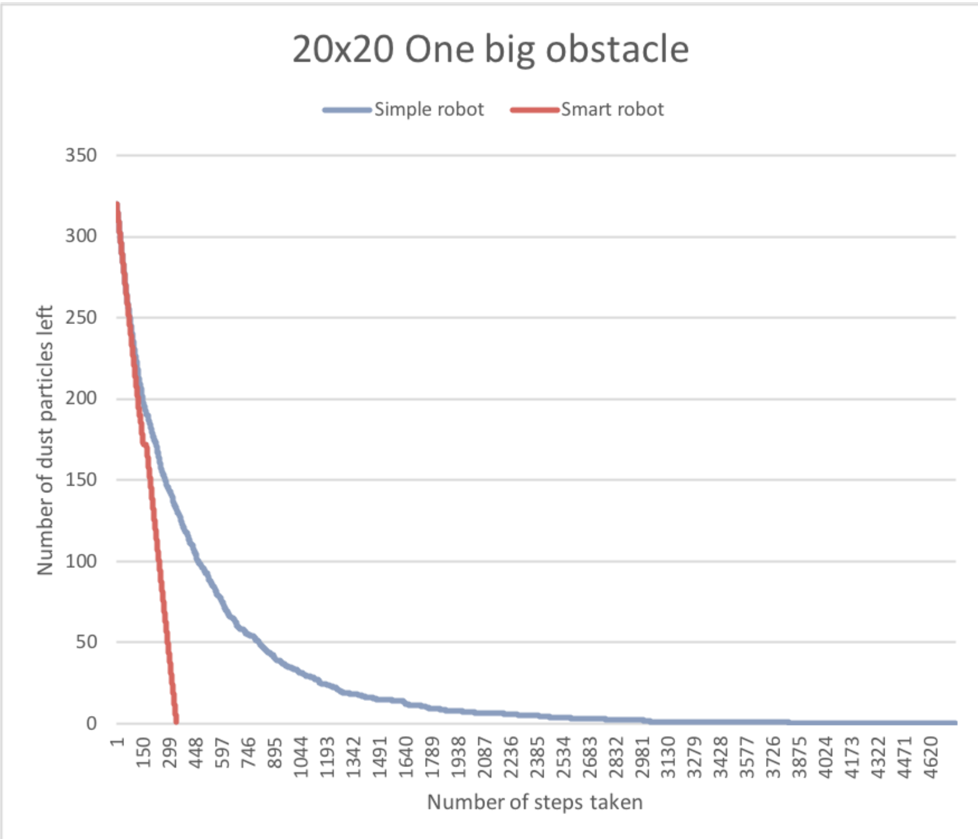

Figure 9. Room 20x20 with one big obstacle.

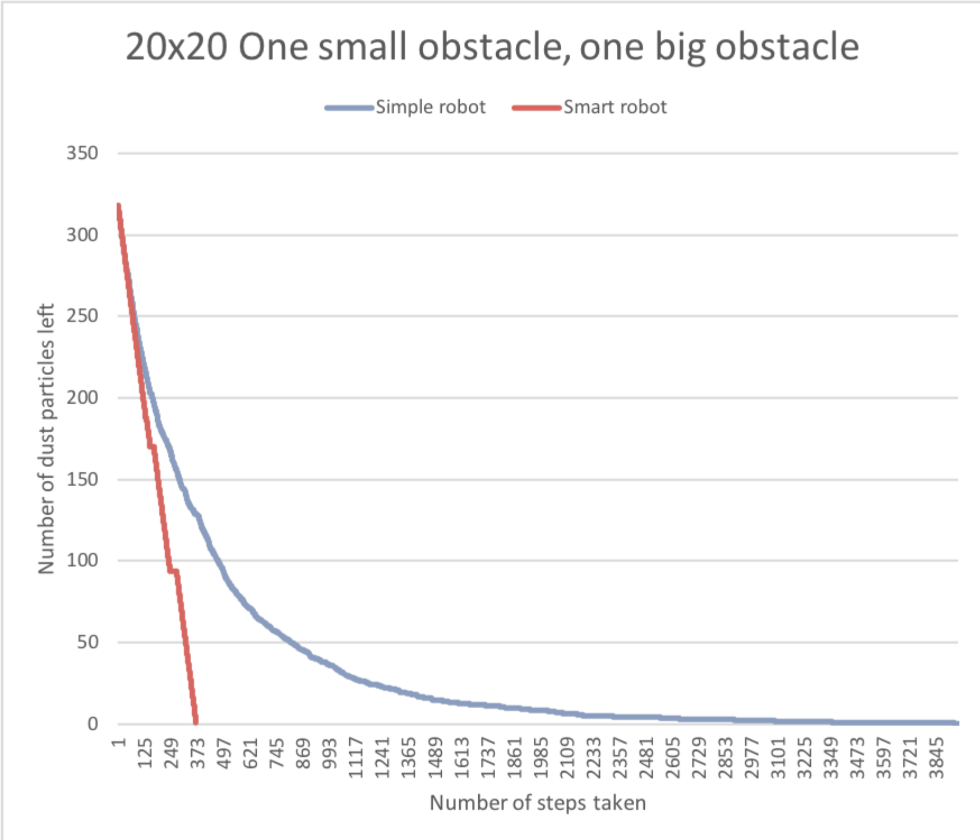

Figure 10. Room 20x20 with one small obstacle and one big obstacle.

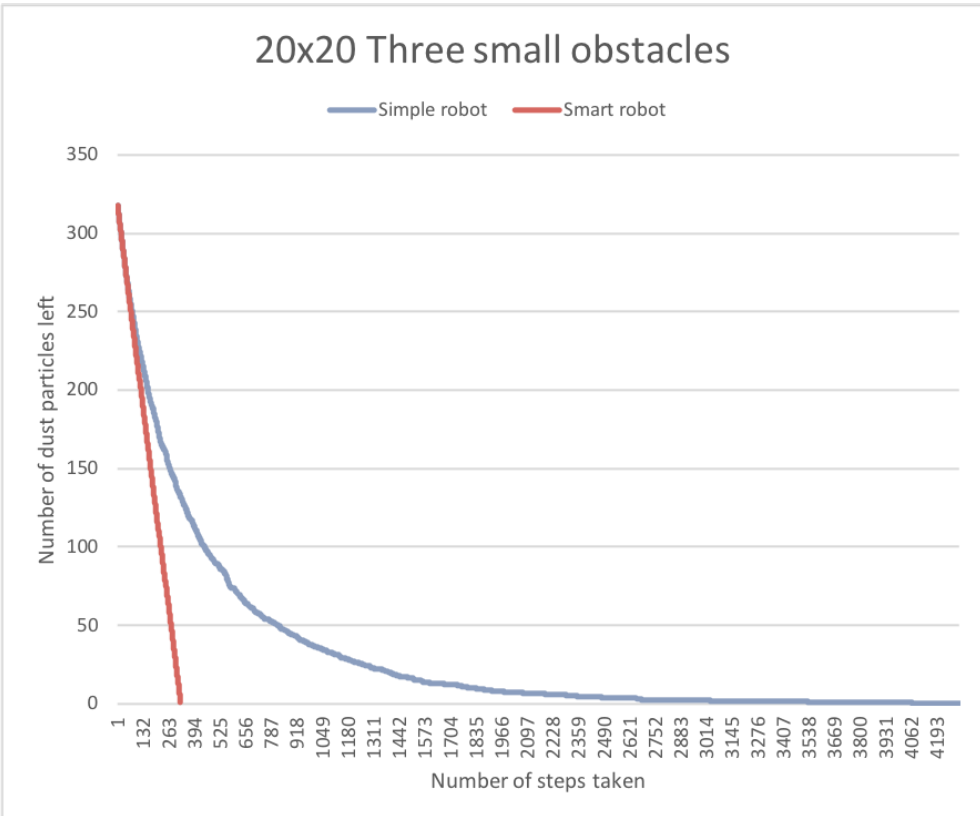

Figure 11. Room 20x20 with three small obstacles.

Chapter 6

Discussion

This chapter discuss the results, the simulations, robotic vacuum cleaners in general and future research.

6.1 Result discussion

As seen in the results in Figure 3, the smart robot was better in all simulations of the different rooms. Looking at the figure, the results are consistent with the hypotheses. The number of steps taken until the room was cleaned for the smart robotic vacuum cleaner were also significantly lower than the mean of the simple model.

Figures 4 to 11 shows how much more efficient the smarter robotic vacuum cleaner is than the simple robotic vacuum cleaner when it comes to how many dust particles that are left for each step that the different models of robotic vacuum cleaner have taken. When the smart model of robotic vacuum cleaner had finished cleaning the 10x10 rooms, the simple model had more than one fourth of the room left to clean on average, and for the 20x20 rooms it on average had two fifths left to clean. Just as with Figure 3, these figures show how much the smart robot exceeds the simple robot. This not only implies that there is room for improvement when it comes to real-life robotic vacuum cleaners, but also shows to what extent real-life robotic vacuum cleaners that uses a random or semi-random pattern system can be improved in terms of floor coverage.

6.2 Simulation discussion

Due to the fact that the simple robot that was simulated was a simplified version of the iRobot's Roomba 605 described in chapter 2.1.1, and not an exact depiction of the real-life model, combined with the robots being simulated in optimal and simplified environments, it cannot be conclusively said that the random navigation pattern that the iRobot's Roomba 605 uses is inferior to a more sophisticated navigation pattern. However, the results in this study show vastly increased efficiency concerning floor coverage by the changes made to the smarter robotic vacuum cleaner. This improvement implies that these changes could have at least some, and possibly major, positive effects on robotic vacuum cleaners in reality.

6.3 General discussion

When robotic vacuum cleaners are compared in reviews, the winning models often have more advanced hardware than IR sensors. However, this study has shown that it is not necessarily the cheap hardware, the IR sensors, that prevents these models from topping the lists, but rather the navigation pattern. If models using IR sensors instead implemented navigation patterns similar to the one in this study, they might perform better in tests and could still hold their low price.

6.4 Future research

With more time and data, a more certain answer could be given to what specific changes that should be made to a simple navigation pattern to make it the most efficient. It would be interesting if future research tested different navigation patterns on real-life robotic vacuum cleaners and real-life environments with more complex obstacles.

6.5 Summary

The fact that multiple numbers of simulations showed similar results supports the idea that there are changes that can be made to the navigation patterns of the models of robotic vacuum cleaners using IR sensors to increase their floor coverage. This indicates that robotic vacuum cleaners can be made both cheap and efficient when it comes to floor coverage.

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Appendix A

Layout of the environments

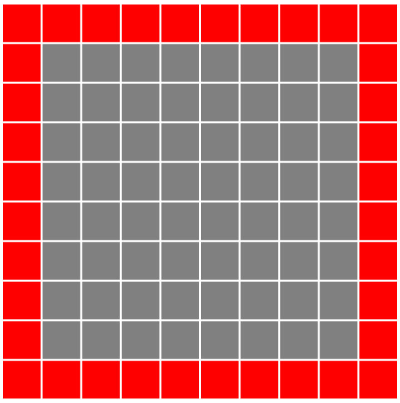

Figure A1. Room 10x10 with no obstacle.

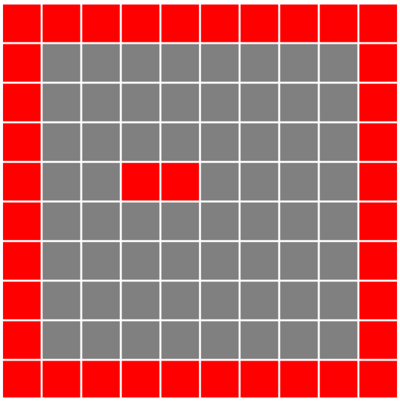

Figure A2. Room 10x10 with one small obstacle.

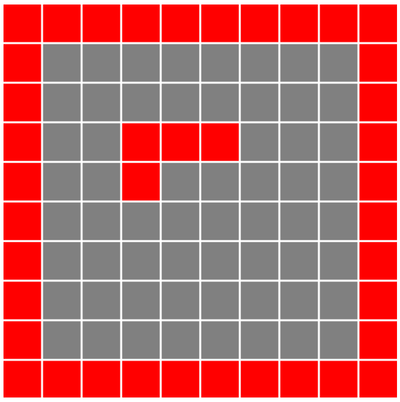

Figure A3. Room 10x10 with one big obstacle.

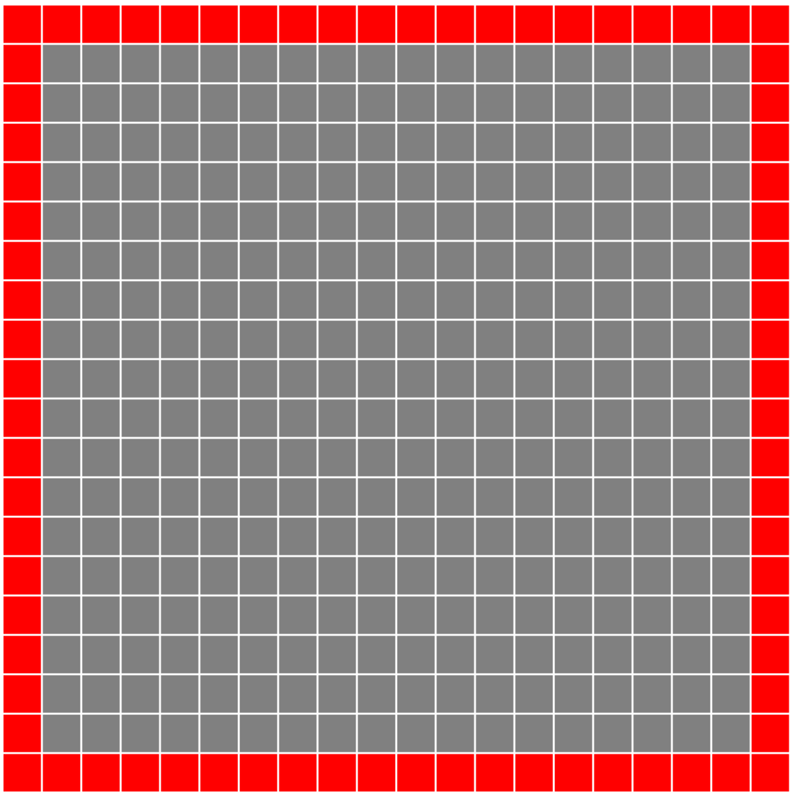

Figure A4. Room 20x20 with no obstacle.

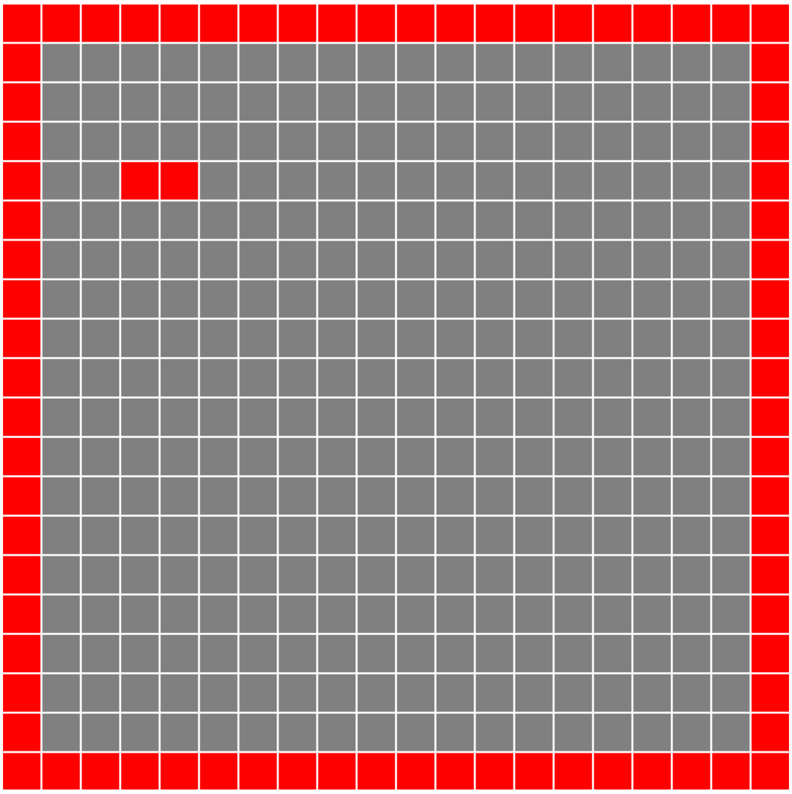

Figure A5. Room 20x20 with one small obstacle.

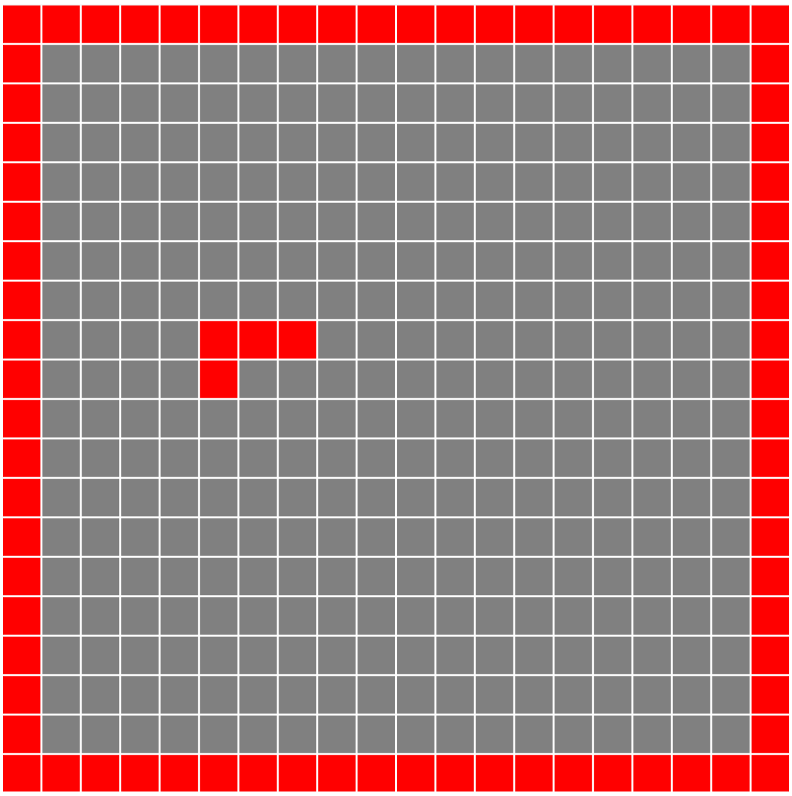

Figure A6. Room 20x20 with one big obstacle.

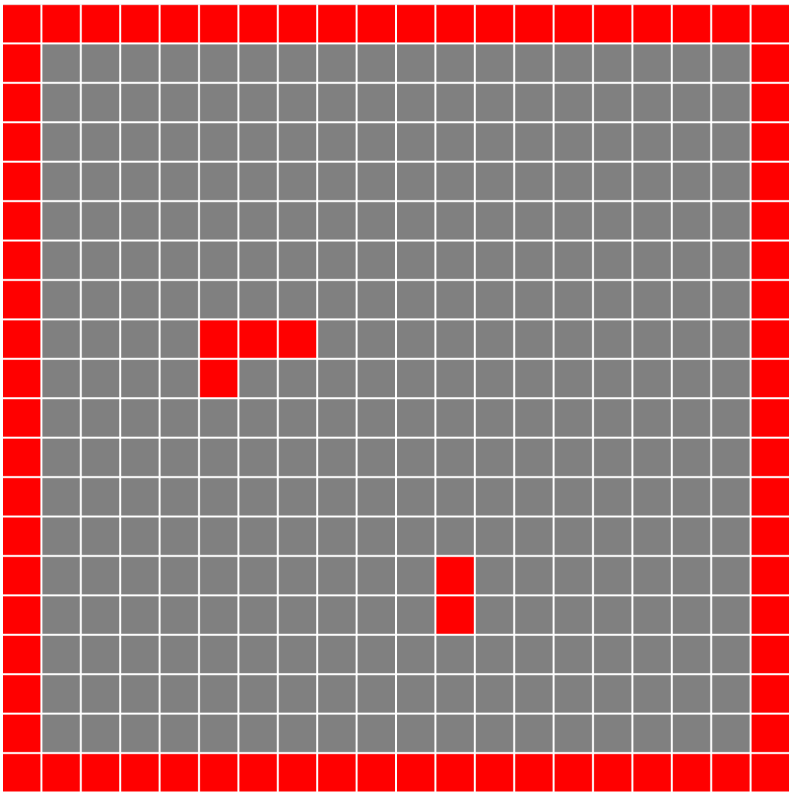

Figure A7. Room 20x20 with one small obstacle and one big obstacle.

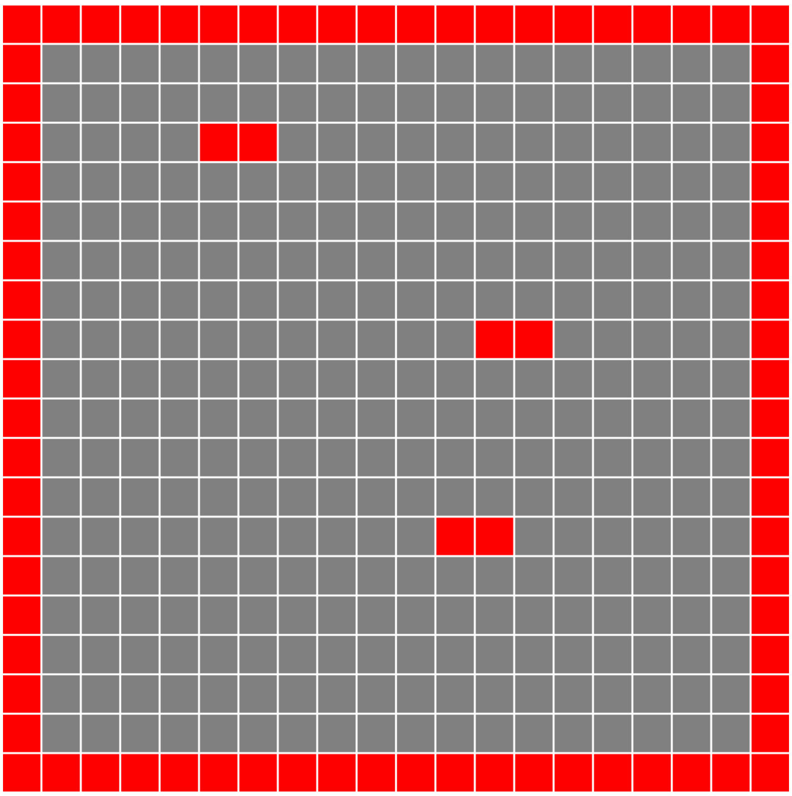

Figure A8. Room 20x20 with three small obstacles.