MASTER

Robotic tiling of rough floors
a design study

Jongeneel, J.P.R. (Roelof)

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Robotic tiling of rough floors: A design study

J.P.R. Jongeneel

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Master's thesis

Eindhoven University of Technology
Department of Mechanical Engineering
Section Dynamics & Control

Supervisor:	Prof.dr. H. Nijmeijer
Coach:	Dr.ir. P.C.J.N. Rosielle
Committee members:	Dr. D. Kostić
	Prof.dr.ir. J.J.N. Lichtenberg

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Preface

This report is the result of a Master thesis project, carried out at the Constructions and Mechanisms group at Eindhoven University of Technology.

I am grateful to Professor H. Nijmeijer for being my supervisor and giving me the opportunity to finish my Master's at the Dynamics and Control section.

Special thanks go out to Nick Rosielle for coaching me and sharing me his great experiences on design principles and projects. I also would like to thank my colleagues at the Constructions and Mechanisms group for their input and for letting me in on their various projects.

Furthermore, thanks to Jan Feijen from ROC tiling educational centre for teaching me the basics of tiling.

Finally, I would like to thank family and friends for their support throughout the past year.

Roelof Jongeneel

Eindhoven, August 2010

Summary

Installing floor tiles is a labour intensive job. It requires a tiler to sit on his knees and bend over to place a tile in front of him. This report, as a result of a Master thesis project, outlines a study on mechanising and automating tiling, and presents a conceptual design.

Firstly, applications of ceramic floor tiles are surveyed and the process of manual tiling is observed. A common method for tiling construction floor areas is thick-bed tiling: Tiles are set in a bed of mortar with 3 to 5 cm thickness.

A modular robot design is chosen. A mortar robot rides on the rough load-bearing construction floor and applies an approximately 300 mm wide strip of mortar. A tiling robot follows and places a row of tiles.

The major processes performed by the mortar robot are briefly discussed. These are: applying a render coat, applying and compacting the mortar, and scraping off of the laid strip of mortar.

Preliminary to the design of the tiling robot, its desired speed of tiling is determined and an estimation is made on the permissible tile placement inaccuracy. Experiments are conducted to deliberate on bonding techniques and to establish what magnitude of force is needed to fix a tile.

The presented design of the tiling robot consists of a rubber track undercarriage and a horizontally suspended body. While the robot drives forward with a constant motion, the heavy suspended body is actively controlled to remain horizontal and to follow a straight line. This makes that all tiles, loaded on the body in cartridges, are positioned with respect to the floor simultaneously. From the body's defined position, tiles are applied statically determined with a fixed downstroke to the mortar bed.

An absolute measurement system is made-up from laser systems, marking out the straight line. A vertical line laser is set up at the beginning of a row. A horizontal laser level on a tripod provides a height reference for the two robots. The lasers are set up and aligned by an operator.

A body suspension is suggested, consisting of air springs for vibration isolation and electromechanical actuators for position control. The static and dynamic behaviour of the air-sprung body is analysed.

In conclusion: A technically feasible solution is found for automated tiling by robots. Detailed design of the tile placement device is initiated.

Samenvatting

Het leggen van vloertegels is arbeidsintensief werk. Een tegelzetter moet op zijn knieën zitten en voorover buigen om een tegel te kunnen plaatsen. Dit rapport, als afsluitend resultaat van een master-afstudeerproject, omvat een onderzoek naar het mechanisch en geautomatiseerd zetten van tegels en presenteert een globaal ontwerp.

Als eerste is onderzocht waar keramische vloertegels worden toegepast en zijn de processtappen van het zetten van tegels bekeken. De gebruikelijke methode voor ruwe betonvloeren is het zetten van tegels in dikbed mortel, met een laagdikte van 3 tot 5 cm.

Een modulair ontwerp van robots is gekozen. Een mortelrobot rijdt over de ruwe vloer en legt een 300 mm brede strook mortel. Een tegelrobot volgt en plaatst een rij tegels.

De belangrijke processen die uitgevoerd worden door de mortelrobot zijn kort beschreven. Deze zijn: het aanbranden van de vloer, het leggen en verdichten van mortel en het afschrapen van de gelegde strook op hoogte.

Voorafgaand aan het ontwerp van de tegelrobot is de gewenste tegelsnelheid berekend en is een schatting gemaakt van de toelaatbare plaatsingsfout. Praktijktesten zijn uitgevoerd om een keuze te maken uit verschillende verlijmingstechnieken en om de kracht te bepalen die nodig is om een tegel te fixeren.

Het voorgestelde ontwerp van de tegelrobot bestaat uit een onderstel op rubberen rupsbanden en een afgeveerde bak. Terwijl de robot vooruit rijdt met een constante snelheid, wordt deze zware bak actief vlak gehouden en op hoogte geregeld, om een rechte en horizontale lijn in de ruimte te volgen. Alle tegels op de bak worden zo tegelijk gepositioneerd ten opzichte van de vloer. Vanaf deze geregelde positie worden tegels statisch bepaald op het mortelbed geplaatst met een vaste hoogteslag.

Met standaard laserapparatuur is een absoluut meetsysteem samengesteld dat de gewenste lijn van tegels aangeeft. Aan begin van een rij projecteert een lijnlaser een verticaal referentievlak. Een horizontale rotatielaser op een driepoot projecteert een hoogtereferentie voor de beide robots. Een tegelzetter stelt de lasers op en lijnt ze uit.

Een ophanging van de bak is voorgesteld met luchtveren voor trillingsisolatie en elektromechanische actuatoren voor positieregeling. Het statisch en dynamisch gedrag van de luchtgeveerde bak is onderzocht.

Tot besluit: Een technisch haalbare oplossing is gevonden voor het gerobotiseerd zetten van tegels. Een begin is gemaakt met de uitwerking van de tegelplaatsingsmodule.

Contents

Definitions

Coordinate System

Throughout this report, a coordinate system with the corresponding sign convention is used as defined in Figure 1.

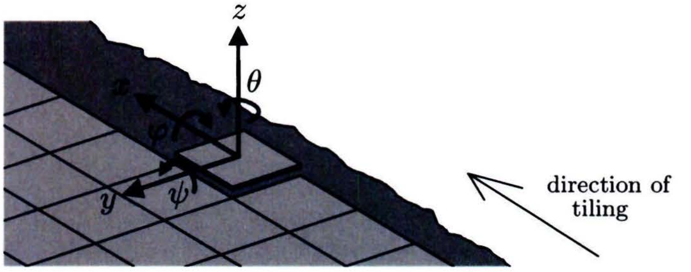


Figure 1: The assigned coordinate system with respect to a tiled floor.

Abbreviations

COG	Centre of gravity
DOF	Degree(s) of freedom
FEM	Finite element method
GPS	Global positioning system
OEM	Original equipment manufacturer
PLC	Programmable logic controller
PSD	Position-sensitive detector
ROC	Regionaal opleidingencentrum
TU/e	Eindhoven University of Technology
UV	Ultraviolet

Bilingual Tiling Glossary

apply paste bond coat	pappen
apply powder bond coat	poederen
bond coat	contactlaag
compacting	verdichten
curing	uitharden
embedment	inbedding
expansion joint	dilatatievoeg
grout	voegsel
lime	kalk
mortar	mortel
notched trowel	gekamde troffel
open time	opentijd
plasticiser	kunstharsdispersie
render coat	aanbrandlaag
screed	dekvloer
thick-bed	dikbed
thin-set	dunbed
trowel	troffel

Chapter 1

Introduction

Since humans began to settle down in steady residences, they have a wish for covering their floors for solidification and decoration. An old way of flooring is using ceramic tiles. Ceramic tiles have been found in ruins of over 6000 years old and are also found in the pyramids in Egypt. Even though there are many other floor covering materials and techniques nowadays, ceramic tiling is still popular and widely applied around the world.

Figure 1.1: A choice collection of ceramic tile applications.

1.1 Motivation

While many processes and labour activities are being mechanised or automated, the process of laying tiles is still a labour intensive job. From an ergonomic point of view, the labour circumstances for the tiler are very bad. About 10% of the tilers are disabled before they reach the age of 52 [Abb01].

As visible in Figure 1.2, the installation of a floor tile requires the tiler to sit on his knees and bend over to place the tile in front of him. It causes an unnatural load on the spine and large supporting forces on the knees. Kneeling moreover cuts the blood circulation to the lower legs and for the long-term, it can cause irritation of the knees.

Due to the bad labour circumstances, the profession of tile-setting is becoming less popular. This brings about that skilled professionals are hard to find. The use of mechanical tools and automated systems will help to lighten the labour of tilers. Moreover, the international

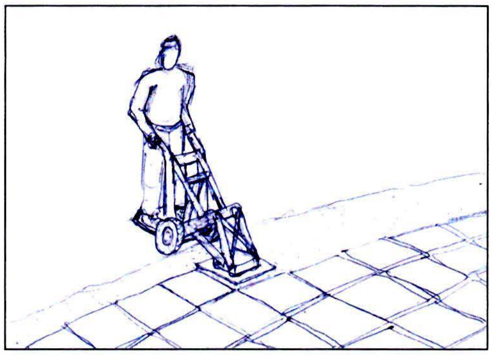
Figure 1.2: A non-ergonomic position can be seen when a tiler places a tile.

competition is high. Tilework is often contracted to workers from low-wage countries. Because of this, the need arises to construct buildings in a faster, cheaper and more efficient way. Deploying robots at the construction site is a way to accomplish that.

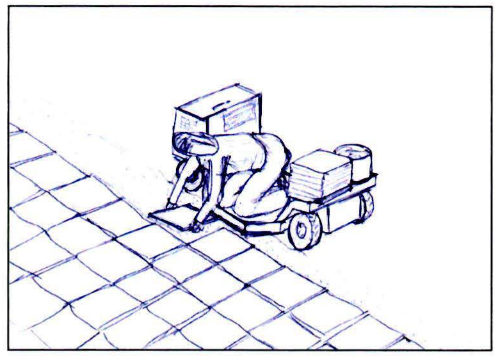
1.2 Project Proposal

This project is aimed to help the tiler and ease labour by means of mechanical assistance. There are various ways this goal can be achieved, ranging from an additional hand tool for the tiler, to an autonomous tiling device taking over most of the tiling job. Within this range, Figure 1.3 shows four conceptual drawings of systems, having distinctive kinds of human interaction.

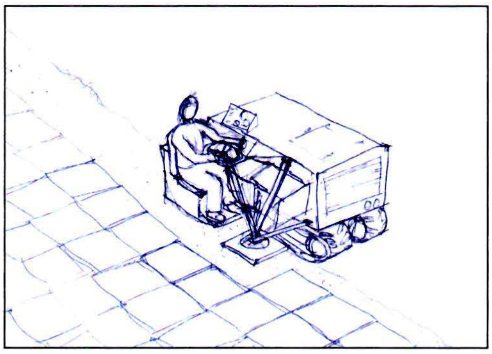
- The tool depicted in Figure 1.3a is a tool for lifting and placing tiles from an upright standing posture. An existing example of such a system is the T-bo developed by Venema [Ven]. It is some kind of hand truck with a tiltable suction device for lifting and dropping tiles; specifically designed for handling large and heavy tiles, typically > 600 mm squared or > 25 kg.
- Figure 1.3b shows a carriage on which a tiler can drive around and place tiles from it. Tiles and other materials are loaded on the carriage. The carriage preserves the tiler from crawling over the concrete floor and lugging tiles. However, it still does not prevent the tiler from working in a non-ergonomic position.
- The carriage of Figure 1.3c gives the tiler a better position by means of a seat. Handling and assembling tiles is performed by the robot, whereas the tiler takes care of positioning and alignment. The increased complexity of the tiling machine will result in a higher cost price. However, due to the eased labour, tiling throughput can be increased.
- The ultimate way of robotisation implies a fully autonomous tiling robot, as depicted in Figure 1.3d. It enters a room and tiles itself back toward the exit, delivering a perfectly tiled floor without any human assistance. It must be able to autonomously determine a tiling route towards the exit, periodically reload itself with tiles, assess them and cut tiles on edges.



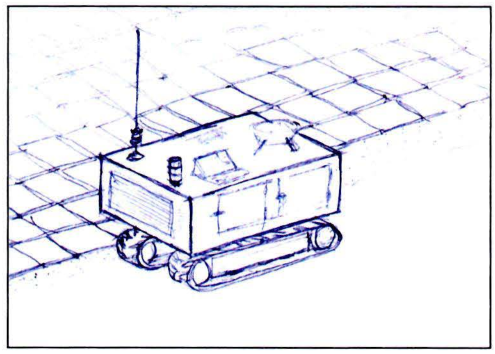
(a) Tool for single tile handling



(b) Carriage moving the tiler and materials



(c) Tiler is driving robot and manipulating tiles



(d) Fully autonomous tiling robot

Figure 1.3: Four conceptual systems with different kinds of human interaction.

Considering tiling branch developments, experiences of tilers, economical feasibility and the search for a feasible, sustainable and sought-after solution; a setup in between Figure 1.3c and 1.3d has been proposed and chosen to be developed within this project.

The tiling robot does not need to be autonomous, as it is not the intention to make tilers superfluous, but to assist them. Requiring the robot to be capable of doing everything, including edges and other difficult jobs, will increase complexity and cost price in a non-proportional way. For this reason, the tiling robot will tile the large areas but leave the edges and difficult niches to be tiled manually by a skilled tiler. Furthermore, at this stage, the robot is being supplied with assessed tiles by an (assistant) tiler. A future possibility is appending the robot with an on-board tile assessment system. Even the extension to an autonomous robot could be possible.

Giving place to a tiler, seated on the robot and manipulating tiles, requires an interface to enclose the 'human-in-the-loop'. Automating the positioning and placing of tiles, eliminates this and moreover makes the tiler free to do other tiling work. For automated positioning of tiles, an actuation system with a feedback measurement system is essential. A human tiler can set up and initialise the measurement system.

This report will elaborate on the design of the just proposed robotic system. At the end, conclusions will be drawn on the general, but more specific on the technical feasibility of a tiling robot, accompanied by directions for further research.

Chapter 2

Project Outline

After proposing a robotic system to assist tilers, various aspects on tiling are examined. With this, first design choices are made. This chapter starts with a quick survey on other robotic floor tiling projects.

2.1 Related Research Activities

Throughout centuries, the development of mechanical tools and equipment lightens a lot of labour in construction. Since decades, research explores robotisation in construction. An overview of construction robots in various phases of construction can be found in [Rob04] and [BaA08].

In contrast to the tiling industry, mechanisation and robotisation already takes a lead in the pavement industry; as a result of which machine laid paving is becoming more and more common. Since 2006, the Dutch Labour Inspection even requires that all block paving jobs larger than 1500 m^2 are to be machine laid [OBN]. Some examples of paving machines can be found in Appendix B.1.

While the tiling and paving industries seems to be familiar, concrete blocks are more dimensionally stable and thus can simply be laid against each other, whereas ceramic tiles have to have a spacing in between to clear away dimensional tolerances and stress relief for expansion. Furthermore, compared to outdoor pavement, aesthetic aspects are of high demand for (usually indoor) tiled floors. The mentioned aspects are presumably some reasons that machines are not utilised for automated tiling.

In recent past, several research activities have taken place to develop a floor tiling robot. None of these projects however resulted in a feasible or commercially available machine. Next, three projects are mentioned on robotic floor tiling.

2.1.1 Pittsburgh, 1996

[ASW96] draws up a conceptual design of a mobile robot for automatic installation of floor tiles. The paper outlines and motivates the configuration of what a robot like this should look like. It starts observing the manual tile laying process and outlines the difficulties and possibilities for automatisation. An average human tiler is observed to place 112 m^2 per 8 hours at a large area of 6500 m^2, including floor preparation, spreading adhesive, feeding tiles and installing tiles. This equals for 300 mm tiles: 24 seconds per tile.

Next, tile placement quality is treated, including a classification of tile installation errors and a suggestion how tiles can be accurately placed using vision cameras. Finally, a choice is motivated for driving the vehicle, handling and feeding tiles and navigation in space. Figure 2.1 shows the conceptual design.

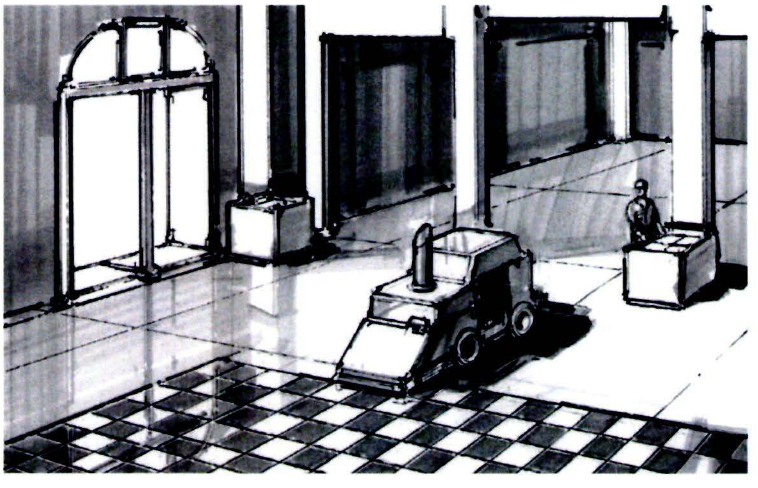


Figure 2.1: Conceptual design of a mobile robot for automatic tiling. [ASW96]

2.1.2 SHAMIR Project, 2000

The SHAMIR Project is originated in Israel at the National Building Research Institute in Haifa. The general concept of SHAMIR (Surface Horizontal Autonomous Multipurpose Interior Robot) is that of a multi-purpose robot, able to perform several horizontal surface construction tasks such as grinding, coating and covering floors [Nav95].

In [Nav00], the development of a floor-tiling module is described. It is to be mounted on the SHAMIR mobility platform. A conceptual design is outlined. Ceramic tiles are set directly on a self-levelling concrete slab. Tile placement is accomplished by making use of a six degrees-of-freedom robotic arm, mounted on the wheel carriage. Feedback signals are obtained by a computer vision system. The robotic system is examined and yields a simulated productivity of two to five times higher than manual tiling. Tile handling and video processing are tested on an experimental setup.

2.1.3 CRAFT Project, 2000

Around the year 2000, the CRAFT project has been carried out, investigating the possibilities for mechanising ceramic tiling [Abb01]. The project was a cooperation of several companies originating from different disciplines. Tile laying companies, tile manufacturers, industrial automation companies and the department of Architecture, Building and Planning from Eindhoven, University of Technology were involved. Next to developing and building a prototype tiling robot, solutions have been explored in adapting tiles as well as mechanisation and automation of spreading a mortar bed and placing tiles.

The general idea of the CRAFT project is to lay down a mortar bed by an automated mechanical device. Next, to lay down tiles, a standard industrial robotic arm is used. This robotic arm is mounted on a carriage, driving over the tiles. It picks up tiles from the carriage and places them on the mortar. The prototype is shown in Figure 2.2.

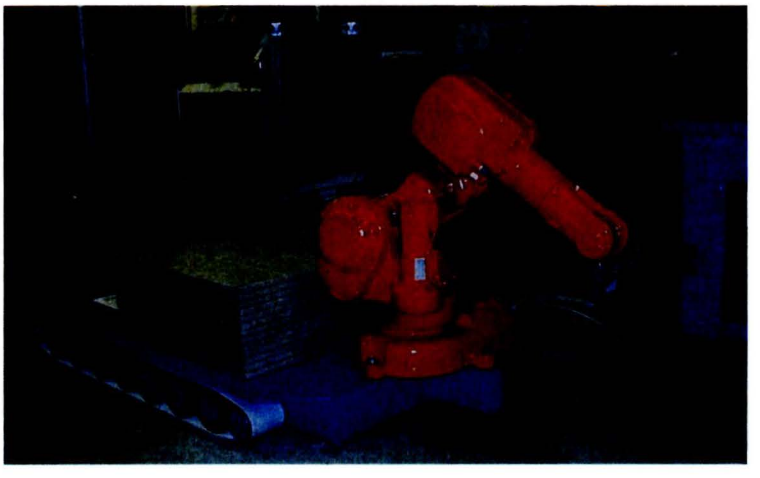


Figure 2.2: The prototype robot of the CRAFT project. [Abb01]

2.2 Project Definition

2.2.1 Fields of Application

As discussed in Section 1.2, the tiling robot is predetermined to tile only the straightforward areas and leave the edges to be tiled manually. For this reason, it will not be cost-effective to employ a robot to tile small floor areas, such as bathrooms, living rooms and probably even small supermarkets. In such fields of application, a lot of time is spent for preparing the robot, compared to the effective tiling time and the time spend for manually tiling the remaining areas. Recovering investment costs is more difficult.

The focus of the new robot design, will be on large floor areas (100 m^2 up) such as supermarkets, shopping malls, factories, swimming pools or airport and train terminals.

2.2.2 Type of Adhesive

For adhering tiles to the floor, two methods are commonly used – at least in The Netherlands – depending on the subjected floor conditions. Consider also Figure 2.3.

Thin-set mortar is probably most commonly used nowadays. Available as dry powdered or premixed, it is spread on the floor and combed with a notch trowel. As this layer is only a few millimetres thick, it is not appropriate for adjusting the level or flatness of the surface. A flat plane substrate is required on which only minor height adjustments can be made and tile thickness variations can be smoothed away. The flat plane substrate can either be a screed or an old tiled floor and in some situations it is possible to give the load-bearing floor a smooth finish suited for tiling, but this is rarely applied. A tile should be pressed on the floor with a slightly sliding motion.

A thick-bed mortar layer is capable of levelling out unevenness and incorporating slopes, for example towards a drain. The mortar layer is usually 3 to 5 cm thick, and 7 cm when a hydronic heating system is incorporated. Thick-bed mortar consists of an earth-moistened sand/cement mixture and is spread on the floor using a trowel. For adhering the mortar bed to the floor, a render cement slurry has to be spread on the floor's surface. On top of the levelled and compressed thick-bed, a bond coat is applied, similar as a thin-set.

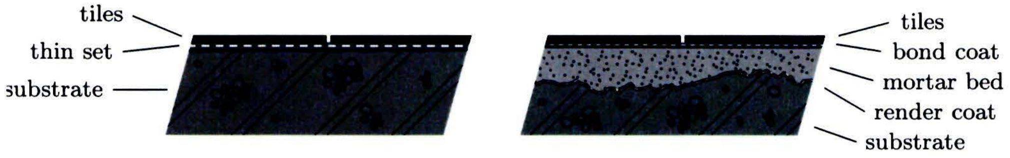


Figure 2.3: Structure of thin-set (left) and thick-bed (right) installation.

Laying tiles on a thick-bed is a bit more work compared to thin-set tiling. It eliminates however the process of laying a screed, which requires four weeks to cure before it can be tiled. From construction time management perspective, waiting time is not desired. The latter makes thick-bed tiling a common method at large construction sites.

As the focus of this project is on large floors, the method of installing tiles on thick-bed mortar is chosen for the new flooring robot design. This offers a complete solution for converting a rough concrete floor into a superbly tiled floor.

A dual mode robot, capable of installing tiles on a thick-bed or either using the thin-set method, would be regarded as a plus, though multi-functionality is not given priority at any price in this project.

2.2.3 Manual Process of Thick-Bed Tiling

The manual process of thick-bed tiling is observed. Below, an enumeration is given of the various steps in the process, as illustrated in Figure 2.4.

1. The room is prepared for tiling. The area to be tiled is measured and a tiling plan is set out. The floor is cleaned from rubble and oil.

2. The floor is moistened with a render cement slurry. This ensures that the mortar bed adheres to the concrete substrate. The floor is wetted, strewed with cement powder and spread with a broom.
3. Mortar is spread over the floor. The mortar consists of cement and river sand (ratio 1:4) and sufficient water such that the mixture is earth-dry.
4. Mortar is compacted by slapping it with a trowel and it is flattened with a long bar to the correct height.
5. A bond coat is spread over the mortar to adhere the tile with the mortar bed. Two methods are common, either strewing dry cement powder or spreading a cement paste:
    - Dry cement powder is generally used for tiles smaller than $(0.2\text{ m})^2$ to $(0.4\text{ m})^2$. The flat mortar bed is sprinkled with water using a watering can. Then, dry cement powder is strewed out. It is left for about some minutes to let the cement absorb water such that it forms a water/cement slurry.
    - A paste consisting of water, cement and some plasticiser is generally used for tiles larger than $(0.2\text{ m})^2$ to $(0.4\text{ m})^2$. It has a greater levelling capability and air bubble drain off. The render paste is poured out over the mortar bed (shown in the picture). The paste is left for about ten minutes, after which it is combed with a notched trowel.

    Note that the time the bond coat is left for absorbtion may not be too long or it dries out. This is known as the open-time.
6. A tile is placed on the bond coat and fixed with some strikes of a rubber hammer. The strikes ought to be gentle, not to break the tile.
7. In case of cement splashes: These are to be removed from the tiles with water.
8. The tile joints are filled with grout using a rubber trowel. The excess of grout is wiped off with a damp sponge.

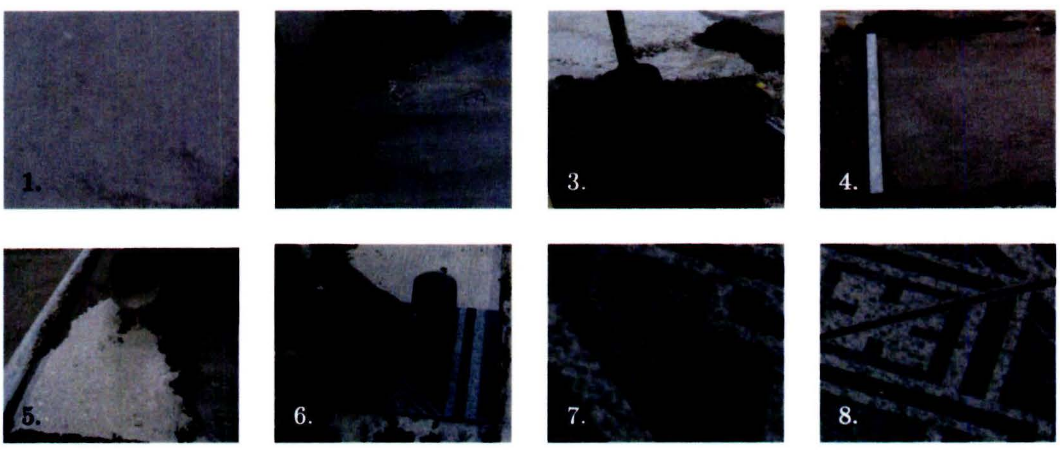


Figure 2.4: The process of manual thick-bed tiling, illustrated in steps.

2.2.4 Expansion Joints

A tiled floor is subjected to expansion and contraction, caused by temperature differences and curing of cement. Expansion joints in the tilework and in the mortar bed allow for this. In any case, structural joints in the underlying load-bearing construction should be extended in the tilework. Furthermore, tilework should be cut off approximately every 8 × 8 m, and even less in case of direct exposure to sunlight.

To create an expansion joint, an empty tile joint is filled with soft sealant, often backed up with foam. It is also common to use an expansion profile, installed either before placing a tile or when a floor is laid and the mortar is not cured yet. Figure 2.5 shows the cross-sectional structure of various types of expansion joint.

As expansion joints can also be installed after tiling, the robot can continuously applying mortar, but should leave a wider joint space during tiling periodically.

Figure 2.5: Various types of expansion joints: An embedded expansion profile or a joint sealant, either applied in thick-bed mortar or thin-set adhesive.

2.2.5 Tile Properties

Floors are tiled with tiles of various sizes, ranging from several centimetres for mosaic floors, up to nowadays trend of 1 m^2 tiles. The subjected ceramic tiles have relatively large dimensional tolerances due to shrinkage during the tile's fabrication process.

It would be impractical, requiring the tiling robot to handle any size. More suitable is to design a robot, able to handle tiles within a range of dimensional sizes, e.g. $(0.2\text{ m})^2$ to $(0.4\text{ m})^2$. Series of robots can be employed for small, medium or large tiles; if not to restrict automated tiling to mid-sized tiles.

For the design as presented in this report, the tiling robot is restricted to the handling of ceramic tiles with nominal dimensions 300 mm × 300 mm and 8 mm thick; without the need to be adaptable, but still be able to cope with dimensional variations. It should further be able to handle any type of ceramic tile: rough and porous, as well as glossy tiles.

2.3 Design Layout

2.3.1 Riding Surface

It was found during tests with the prototype robot of the CRAFT-project, that tiles deviate from their position, caused by the caterpillar tracks riding over the tiles [Abb01]. This happens especially during turning, but also when riding in a straight line. From the same project it was concluded earlier that riding on the mortar bed is not possible either, as fresh mortar cannot withstand the weight of the robot. The weight of the robot was set to 500 kg including carriage, manipulator, controller and stack of tiles [HUK01].

It is not expected, that the new design tiling robot can be much lighter or that the support contact area can be enlarged. Considering this, it has been decided neither to ride over the tiles nor the mortar bed, but rather next to it on the rough concrete construction floor. The robot then lays a strip of mortar and places a tile on top of it.

The mortar laying and tile placement devices are to be positioned next to the tracks or wheels and thus have an overhang. This overhang is to be kept small for a compact and more stable robot.

The row of tiles is placed over two strips of mortar to form a stretching bond. Figure 2.6 shows a cross section of a tiled floor, together with the imaginary shape of the tiling device and caterpillar tracks (dotted). The tiling process started with a mortar strip without placing a tile. The width of half a tile is taken into account on the tiling robot for the overlap of tiles, decline of the mortar bed and clearance to the tracks.

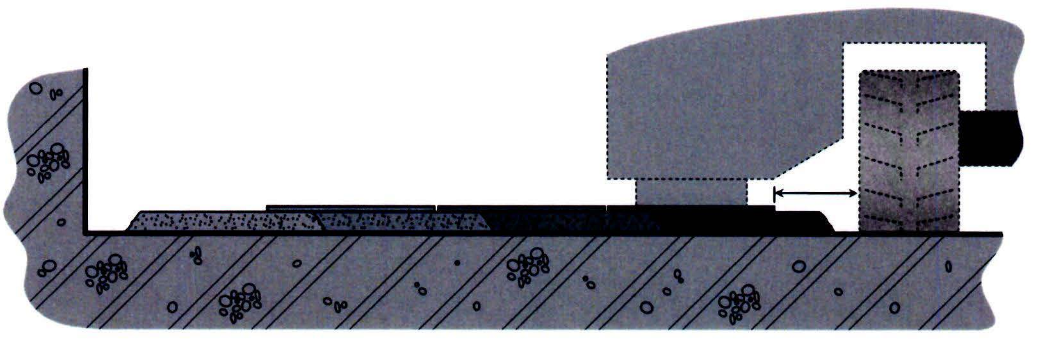


Figure 2.6: A tiled floor will be built up from series of mortar strips and tile rows placed on two of those strips.

2.3.2 Modular Robot Design

Now, two tasks can be distinguished, namely to complete the task of laying down a strip of mortar and placing a row of tiles. Those tasks can be hosted in one machine, or two (smaller) modules can each perform one task. Smaller robots are easier to manoeuvre and as their projected floor coverage is smaller, they can tile closer to the wall and within small niches; thus leave less area to be tiled manually.

A modular robot design has the ability to deploy the mortar robot and tiling robot separately from each other. This can be useful if one of the modules is down, or if specific tiles cannot be laid by the robot because of size, structure or other reasons; then a mortar bed can still be laid by the mortar robot.

On the other hand, tiling a screed floor or renovating an existing floor using thin-set adhesive, can be done easily by employing only the tiling module with an additional thin-set adhesive dispenser. Prior to placing the tile, a notched film of thin-set is laid on the mortar screed.

A drawback of the modular choice is the increased work for operation, as now two robots instead of one have to be provisioned and aligned for a new strip of tiles. However, separating the functions gives more freedom during operational service. The two processes do not strictly have to run at the same speed. Having a time between spreading the contact layer consisting of cement and water, and placing the tile, allows the cement to absorb water.

Separating the two tasks also ensures that the process of mortar spreading and compacting – it induces disturbance forces on the machine – does not influence the more delicate task of tiling. Hosting the two tasks in one machine would require attention to sufficiently decouple the two processes.

2.3.3 Design Sketch

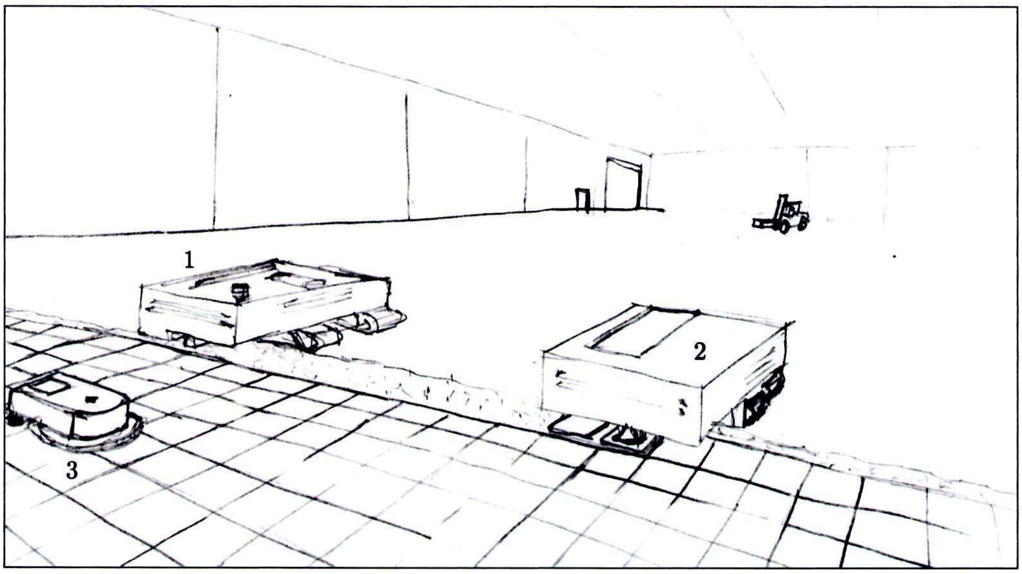


Figure 2.7: The mortar robot (1), tiling robot (2) and finishing robot (3) at work.

Figure 2.7 shows a conceptual drawing of the mortar robot (1) and the tiling robot (2) tiling a floor. For finishing the floor, the joints between tiles are to be filled with grout. To also mechanise this task, a small third robot (3) is imagined to do the grouting job and clean the floor with water. As this module is less high-tech and not primarily needed for automated tiling, it is not further elaborated in this report. Refer to Appendix B.3 for a survey on commercially available grouting machinery that can be deployed.

Furthermore, a forklift truck is needed for supplying the robots with mortar and tiles. To ease the floor preparation phase, a street cleaner is helpful for sweeping the construction floor.

The robots will ride on the rough construction floor. The mortar robot applies a render coat and an approximately 300 mm wide strip of thick-bed mortar. The tiling robot follows, applies a bond coat and installs 300 mm ceramic tiles.

The design of the tiling robot and mortar robot are to be worked out in this report. First, their global design is discussed in Chapter 3 and 4, respectively. Next, in Chapter 5, possible measurements systems are discussed. Chapter 6 elaborates on the robot's static stability and dynamical behaviour. A start on the detailed design of the tile handling and placement device is described in Chapter 7.

Chapter 3

Tiling Robot Design Aspects

This chapter investigates some aspects to come to a design concept for the tiling robot. First, the desired tiling speed is derived from a cost-effectiveness study. Next, the robot's tiling inaccuracy is set to a limit. The next section considers various methods of actual tiling and choices are made. After that, a number of other design aspects are investigated as well.

3.1 Desired Tiling Speed from Cost Perspective

Depending on the speed of tiling by the robot, it can take over the work of one or more tilers. Generally, only when the investment of a tiling robot is profitable, a tiling company is in favour of automated tiling.

3.1.1 Cost-Effectiveness

In Table 3.1a, a very rough estimation of investments is made. The cost price of the two robots is estimated to be € 800,000. Assume, the investment should be payed back within three years. In those three years, salary is saved of human tilers. The savings are drawn up in Table 3.1b. Normally, an investment is not interesting when there would be no profit: A desired profit of 30% is included.

Remember that the robot would also result in less inability to work, less health insurance premium and decreasing the shortage of skilled tilers. Those profits are not included in Table 3.1b as they do not directly benefit the tiling company, though they will benefit the community.

Dividing € 1,204,000 by € 114,000 gives the factor that the robot should tile faster than one human professional tiler, which is in this case about 10.

Economic investment value			€	800,000
Number of years to write-off	3	yrs		
Interest rate	6	%		
Interest over 3 years			€	96,000
Operational costs over 3 years			€	30,000
Subtotal			€	926,000
Desired benefit	30	%		
Commercial investment value			**€**	**1,204,000**

(a) Investment of robots.

Annual gross salary tiler			€	25,000
Factor for social security costs	1.30	[-]		
Factor for retirement costs	1.15	[-]		
Subtotal			€	36,250
Savings on sick leave	5	%	€	1,800
Annual savings per tiler			€	38,000
Savings over 3 years			**€**	**114,000**

(b) Savings on salary.

Table 3.1: Savings and investment model for determining the cost-effectiveness.

3.1.2 Manual and Automated Speed of Tiling

An observation of manual tiling is described in [ASW96]. A 6500 m^2 supermarket is tiled with 300 mm × 300 mm tiles, placed onto a thin-set. Omitting the time needed to determine the tiling plan and stake it out on the floor, the average human tiling efficiency lies around 14 m^2 per hour or 24 seconds per tile per installer. This includes sweeping the floor, spreading the adhesive, transporting the tiles and placing them. The latter step (that is installing a tile) takes 8 seconds.

The overall efficiency of 24 seconds per tile per installer could be verified quite well by the author of this thesis, while observing tilers renovating a local supermarket.

Comparing the two methods for adhering tiles: Placing tiles on thick-bed mortar takes about twice the time of placing tiles on thin-set ([Arb83], [JFe]).

Taking all factors into account yields a budget of 5 seconds per tile for robotic tiling. Subtracting initialising time, refilling time and driving idle, the robot will be designed on placing one tile every 2 seconds in tiling mode.

3.2 Desired Placement Accuracy

To obtain a high quality tiled floor, the placement of tiles needs to be sufficiently accurate. Next to tolerances in joint width and surface flatness, which are describing the quality of tiling, size and shape aberrations of tiles have to be considered.

3.2.1 Quality of the Tiled Floor

Consumer satisfaction in the construction quality management have been studied in [For06]. This study is focussed on finishes in construction such as tiling, brickwork, paving and jointed façades and tries to develop a method for assessment of construction quality, involving the perception of consumers. For illustration, an experiment is carried out where consumers assess tiled floor areas at 50 different projects. It turned out to be that consumers accept up to 70% variance in joint widths before finding the work 'ugly' and that they accept at least three 'ugly' joints within an area of 5 m^2.

As consumer satisfaction is rather subjective, a more quantitative quality description is desired. Though there are standards describing the flatness of screeds, there are none for describing the quality of a tiled floor. To resolve this, Stichting STABU has drawn up an unofficial standard [STA07]. Construction specifications can refer to this standard, to give clearance in juridical issues. Considering the tiling robot; this standard helps quantifying what is visually regarded as a 'superbly' tiled floor.

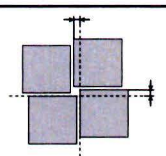
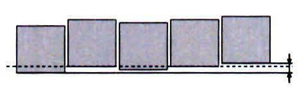
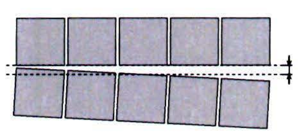
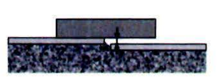
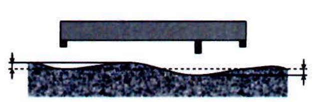
	Deviation of the adjoining tiles w.r.t. the tiling grid	< 1.5 mm
	Divergence of a row of tiles w.r.t. the tiling grid	< 3.0 mm/m and overall < 9 mm
	Divergence of the joint width over a length of 2 m	< 1.5 mm
	Height deviation between adjoining tiles (lippage)	< 1 mm
	Height deviation under a straight edge of 2 m 4 m 10 m 15 m	 < 4 mm < 7 mm < 13 mm < 17 mm

Table 3.2: Alignment and flatness tolerances for average tiling quality, according to the STABU standard [STA07].

The STABU standard distinguishes three groups to qualify the tiled floor. The middle group describes tiled floors which have to satisfy an average visual quality. At least, the robot should be able to tile conform average tiling quality. Table 3.2 gives an overview of the permissable tolerances in joint-width, divergence and floor flatness, for the middle group.

3.2.2 Dimensional Tolerances of Tiles

While baking a tile, the fresh clay shrinks with respect to the shape in the mold. This causes the shape of the tile to be non-straight. The dimensional tolerances on these non-straightness are described in the European norm EN-14411. Measurements on dimensional and surface quality are to be conducted according to ISO-10545-2.

Table 3.3 gives an overview of tile tolerances of a dry pressed tile of class BIa/BIb. Note that in general, the majority of tiles has a better quality than described in the norm.

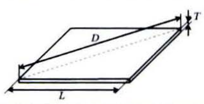
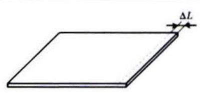
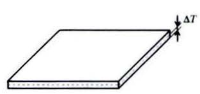
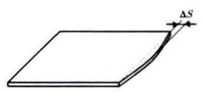
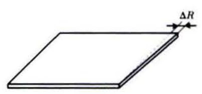
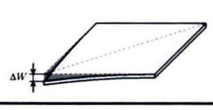
	Description	EN-14411 norm	300×300 tile
	Length and width, $\frac{\Delta L}{L}$	± 0.5 %	± 1.5 mm
	Thickness, $\frac{\Delta T}{T}$	± 5 %	± 0.4 mm
	Straightness of sides, $\frac{\Delta S}{L}$	± 0.5 %	± 1.5 mm
	Rectangularity, $\frac{\Delta R}{L}$	± 0.6 %	± 1.8 mm
	Center curvature, $\frac{\Delta C}{D}$	± 0.5 %	± 2.1 mm
	Edge curvature, $\frac{\Delta E}{L}$	± 0.5 %	± 1.5 mm
	Warpage, $\frac{\Delta W}{D}$	± 0.5 %	± 2.1 mm

Table 3.3: Dimensional tolerances of a tile in percents and in case of a 300 mm × 300 mm tile.

3.2.3 Desired Accuracy of Tile Placement

Knowing the desired quality of tiling and fabrication tolerances, the desired accuracies for placing a single tile on the floor can be interpreted in all six degrees of freedom.

Observing the tolerances describing the floor quality in Table 3.2, one can distinguish placement accuracies with respect to the tiling grid over the whole area; and placement accuracies clearly describing tolerances with respect to adjoining tiles.

The placement tolerance together with half the tile tolerance (a tile's dimensional variation can be divided over the two opposite sides) makes the alignment and flatness of the tiled floor. As placement tolerances and tile tolerances are two uncorrelated sources, that is, they do not affect each other, the root mean square error may be used. Hence, the desired placement accuracy is calculated by

$$\text{placement accuracy} = \sqrt{(\text{alignment tolerances})^2 - (\tfrac{1}{2}\text{ tile tolerance})^2}.$$

The maximum placement inaccuracies are presented in Table 3.4. Tolerances for the alignment and tile dimensions are allocated in a suitable way, to represent them as the maximum permissable error in six degrees of freedom. Note that the mentioned placement inaccuracies are maximum to fulfill the requirements. It is desired that the robot performs better.

DOF	Placement Inaccuracy	Tile Deviance	Alignment Error
x	$< \pm$ 4.4 mm	$< \pm$ 1.1 mm	$< \pm$ 4.5 mm
y	$< \pm$ 4.4 mm	$< \pm$ 1.1 mm	$< \pm$ 4.5 mm
θ	not constrained	$< \pm$ 0.26°	not specified
z	$< \pm$ 3.8 mm	$< \pm$ 2.1 mm	$< \pm$ 4.0 mm
φ	not constrained	not relevant	not specified
ψ	not constrained	not relevant	not specified

(a) Error budget with respect to the overall imaginary projected tiling grid

DOF	Placement Inaccuracy	Tile Deviance	Alignment Error
x	$< \pm$ 0.9 mm	$< \pm$ 1.1 mm	$< \pm$ 1.1 mm
y	$< \pm$ 0.9 mm	$< \pm$ 1.1 mm	$< \pm$ 1.1 mm
θ	$< \pm$ 0.15°	$< \pm$ 0.26°	$< \pm$ 0.20°
z	$< \pm$ 0.4 mm	$< \pm$ 1.1 mm	$< \pm$ 0.7 mm
φ	$< \pm$ 0.08°	$< \pm$ 0.20°	$< \pm$ 0.13°
ψ	$< \pm$ 0.08°	$< \pm$ 0.20°	$< \pm$ 0.13°

(b) Error budget with respect to adjoining tiles

Table 3.4: The desired placement accuracy is calculated from the tile tolerances and alignment tolerances.

3.3 Method of Assembly

Next step in quantifying the tiling system is getting inside in what is needed to firmly fix the tile to the ground. First, the strike of a rubber hammer is investigated. Then, possibilities are investigated for applying a static force on the tile instead of dynamical peak forces.

3.3.1 Strikes of a Rubber Hammer

A moderate tiling strike is given on a load cell with a rubber hammer. The measured response is printed in Figure 3.1, and shows a peak force of 1200 N within a time span of 3.8 ms.

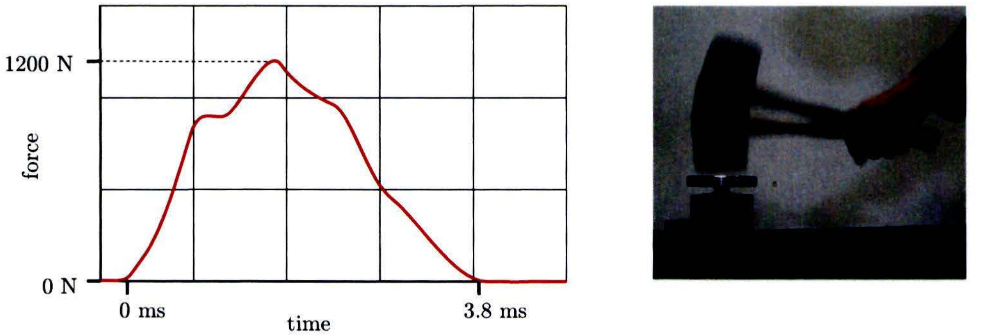


Figure 3.1: Measured response of an average tiling hammer strike.

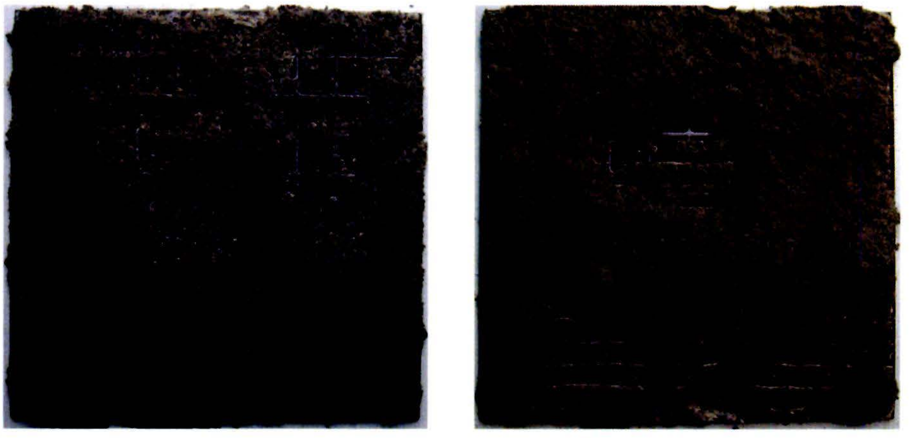
A number of those hammer strikes are given on a tile to adhere it on a mortar bed. The mortar bed is prepared as described in Section 2.2.3. To examine the tile's embedment, the tile is pulled off and its backside is observed. The visual observation of the backside (what area is covered with mortar and cement slurry), as well as the force needed to pull off the tile, are a measure for the embedment and fixation of the tile. For the method of testing and relevant testing conditions refer to Appendix A.1.2.

Figure 3.2 shows the backside of two sample tiles, adhered to a compact mortar bed with either a cement powder bond coat (Figure 3.2a) or a cement paste bond coat (Figure 3.2b).

In practice, 300 mm tiles can be installed using either bonding method, as discussed in Section 2.2.3). Figure 3.2a shows that the tile, bonded by 'powdering', is not fully embedded. The tile of Figure 3.2b shows a better embedment. This difference in tile fixation is also visible in the pull-off force: 60 N versus 90 N, respectively. The aim of tiling is to have full embedment of tiles with the bond coat. A bad embedded tile has a higher risk of breakage and thus lowers the permissable load on the floor.

3.3.2 Assembly with a Static Force

Mechanising tiling can be done straightforward by mimicking a tilers hammer strike and designing a mechanism, giving some controlled strikes with a rubber device. Doing so, undesired vibration will be introduced in the machine which can potentially harm the equipment



(a) Dry cement bond coat. **(b)** Cement paste bond coat.

Figure 3.2: Tiles installed by rubber hammer strikes.

and affect measurements. For this reason, experiments were conducted to test whether a statically applied load would also be sufficient to adhere the tile to the mortar. Applying a static load means that part of the robots own weight will be used to adhere the tile to the mortar bed.

In order to investigate what force is needed to firmly fix a 300 mm $\times$ 300 mm tile, four sample tiles were installed with successive forces of $\{0.4, 0.8, 1.2, 1.5\}$ kN applied to the tiles. Again, refer to Appendix A.1.2 for the method of testing.

The intentions of these empirical experiments are to get a feeling on the suitability of various tiling methods for mechanised tiling, and make design choices. Though every test is performed only once, it still gives a representative feeling on the matter, specifically in a relative comparison.

Figure 3.3 shows the test results of the four tiles, where the bonding coat consists of cement paste. A static assembly force of 0.4 kN already results in a moderate fixation, but a firm fixation is guaranteed at 1.5 kN and above.

The same test is conducted for tiles placed on a cement powder bond coat: See Appendix A.1.3. It follows that these tiles do not adhere at all to the mortar bed with just a static assembly force; regardless of its magnitude.

The physical phenomena when beating a tile – water is dissolved from the slurry and deposits on the tile's back – turns out to be essential for a good fixation. It was hypothesised that prewetting the tile's backside will overcome this problem, but the experiments from Appendix A.1.4 show that this results in no significant difference.

The theoretical background of impulse fixation, is not fully understood and at the same hand is not further investigated.

(a) Assembly force: 0.4 kN.

(b) Assembly force: 0.8 kN.

(c) Assembly force: 1.2 kN.

(d) Assembly force: 1.5 kN.

Figure 3.3: Tiles installed on a cement paste bond coat with a varying static assembly force.

3.3.3 Cement Paste Bond Coat

In general, a powder bond coat is cheaper due to the absence of expensive plasticiser, and less material is used because of a thinner film. However, the latter tests show that tiles laid on a cement paste bond coat yield a much better bonding to the mortar bed than using a cement powder bond coat would. This statement assumes having a well compacted and flattened mortar bed. Leaving a less or no compacted bed, the powdering method might be possible as well, as concluded from Appendix A.1.5.

Stand-alone employment of the mortar robot is proposed for screeding a floor without tiling it. When the tiling robot is employed apart, for example when tiling on a thin-set, an adhesive dispenser needs to be attached on it. As the consistency and method of application for the cement paste bond coat is very similar to that of the adhesive used for thin-set tiling, the dispensing of either of the two coats is hosted on the tiling robot.

Applying bond coat by the tiling robot furthermore has the advantage that bond coat is only applied to the bed where a tile is to be placed. The risk of exceeding the allowable open-time and drying out of the bond coat is eliminated.

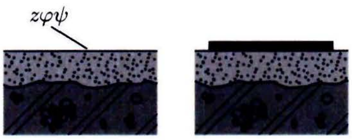
The reason for leaving the bond coat for some minutes, as common in the manual tiling process and mentioned in Section 2.2.3, is to prevent curling up when combing it with a notched trowel. This effect will not happen when dispensing a notched film on the bed from an extruder on the robot and thus making the waiting period most likely not needed.

In case of applying cement powder bond coat, either immediate installation or after period of waiting does not have a noticeable effect on the tile embedment as suggested in Appendix A.1.4.

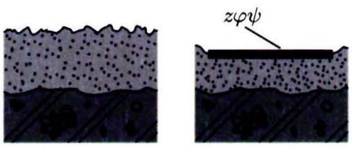
3.4 Allocation of Precision

With the chosen modular design, each module should have a separate measurement system. However, not all systems have to achieve the placement accuracy as described in Table 3.4. The mortar robot for example, does not have to have a x, y, θ-alignment with tile placement precision, but a less accurate measurement and localisation system is sufficient.

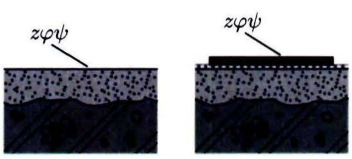
Apart from each robots' localising positioning accuracy, the following three configurations are to be considered for z, φ, ψ- alignment of tiles:



- A perfectly flat and compacted mortar bed is laid by the mortar robot. Next, the tiling robot presses the tiles to the bed with a compliant placement device. Having uncontrolled height and tilt, the tiles take over the flatness of the prepared mortar bed. The final positioning of each tile in all 6 DOF is split over the two robots, where z, φ, ψ-precision is located in the mortar module and the tiling robot does x, y, θ-alignment.



- The mortar robot lays a strip of homogeneous but not fully compacted mortar, a few millimetres above the desired height. The tiling robot places a tile and presses (or vibrates) it to the correct height and in addition compacts the bed. A cement powder bond coat can be possible for bonding. Accurate z, φ, ψ-precision is located in the tiling module.



- The mortar robot lays a strip of well prepared, compacted and flattened mortar. Tiles are placed by the tiling robot at the perfect height and flatness. A cement paste bond coat in between fills the gap and bonds the two together. Accurate z, φ, ψ-precision is needed both in the mortar and tiling robot.

Regarding the first configuration: Though the final z, φ, ψ-positioning of the tile by the tiling robot is said to be open-loop, still it has to stay within the tolerances, as defined in Section 3.2.3. Appendix A.1.6 elaborates on tilting-unconstrained tile placement. The conducted experiment shows tilting deviations larger than the allowed inaccuracies. This may however be (partly) ascribed to testing conditions or inhomogeneous preparing of the mortar bed. Furthermore, tile thickness variations – which are, in worst case, larger than tolerances on the floor quality – are not compensated by the bonding layer but directly visible in the finished floor surface.

The second configuration, requires a less accurate mortar placement device. This is advantageous, as this machine performs a rougher job. Precision in z, φ, ψ and x, y, θ is located in the tiling robot, making it able to perfectly align all tiles' top surfaces. However, compacting the mortar with a fragile tile in between is intuitively very tricky. The risk of a broken tile is higher with inhomogeneous laid mortar. Furthermore, as not all mortar will be compacted to the same extent, the compressive strength of the finished floor is lower compared to a pre-compacted homogenous mortar bed. Because impulsive compacting of the mortar might turn out to be necessary, the tiling robot and the tile itself will then be subjected to vibrations during tile placement. Furthermore, this method has the risk of driving the mortar or bond coat slurry in the space between adjacent tiles. This should be avoided as this space is to be filled with grout later on, maybe of a different colour.

The third option, requires the accurate z, φ, ψ measurement system to be put into effect twice. The two processes (laying mortar and placing tiles) are more separated. As a result of the incompressible prepared mortar bed and the enforced placing of tiles at the desired position, the bonding layer is ought to fill the gap between those. It should be resilient and compressible to cope with the z, φ, ψ placement inaccuracies of both systems. The compressibility experiment described in Appendix A.1.6 shows that the cement paste bond coat is more compressible than a cement powder bond coat, and its compressibility can generally be enlarged by combing the slurry with a wider spaced notched trowel. It is shown in Figure 3.3 that a 0.4 kN assembly force is already sufficient for an acceptable bonding. With the insight of Figure A.8, height differences of at least 1 mm should be able to overcome and still be assure of a good bonding. This budget is likely be enough to overcome the specified cumulative placement inaccuracy (Section 3.2.3) for two uncorrelated measurement systems ($\sqrt{\pm 0.4^2 + \pm 0.4^2} \leq \pm 0.6$ mm) but too small for the worst-case tile thickness variations (± 1.1 mm). Increasing bond coat compressibility or a restriction on tile thickness variation solve this problem, or alternatively, a less flat floor should be accepted.

While all systems have their limitations, the latter configuration is expected to be the safest choice, certainly for developing a new solution for mechanised tiling. As this configuration has a full measurement and positioning system on each robot, it keeps the ability to deploy the tiling robot separately and enables parallel development of the two robots.

3.5 Other Design Aspects

3.5.1 Multiple Tile Placement

Keeping the same throughput, the time between two placement strokes can be enlarged by placing multiple tiles per placement. For example, placing two tiles simultaneously allows a tiling interval of 4 seconds, but it also means a twice as large placement force is needed. Placement force is limited by the weight of the robot, especially if it results in a larger arm from the cumulative placement force to the COG of the robot. Then, it will yield a less stable machine or a larger and heavier robot.

Placing a set of tiles increases the risk of visual appearance of regular patterns in the finished tiled floor. The set of tiles which is placed simultaneously can be perfectly aligned on the robot, however a second set has to be aligned to the adjacent set as good as the alignment of the set itself and the placement device must not show any abberation.

For the sake of eliminating risks of irregularities in the tiling pattern as well as keeping the robot compact, it is chosen to place one tile per tiling stroke (with a cycle time of 2 seconds).

3.5.2 Cartridges Containing Tiles and Adhesive

Ceramic tiles are usually packaged in cartons, in quantities of just over 1 m^2 in a box; that is 12 pieces of 300 mm squared tiles, weighing almost 20 kg.

The tiles are to be loaded on the tiling robot, creating a buffer of tiles from which they are applied to the floor one by one. A cartridge is suggested to contain the buffer for easy transporting and recharging. The design of the cartridge is such that it can be picked up by the forks of a lift truck.

The order of tiling the subjected floor area will be row after row. Because it is better to have a constant, uninterrupted motion during tiling, all tiles needed for this row have to be loaded on the robot beforehand. Prior to tiling, there is a time for recharging and rearranging the robot for a new row.

Tiles have to be unpacked, undergo a visual inspection, mixing tiles from different batches and picking out broken and damaged ones. With the use of tile cartridges, this process can be done independently during tiling, after which a full cartridge can be quickly exchanged during rearrangement time. In the future there are opportunities in association with tile manufactures, regarding the delivery of tiles already loaded in such refillable cartridges.

Tiles are to be stacked vertically on their edge inside the cartridge. This prevents a stack of horizontal tiles pressing on the lowest one. Moreover, a vertical stack lets tile dust and flakes fall down, whereas, in case of a horizontal stack, it may remain lying on the tile's top surface and affect a statically determined pick up and obstruct clamping with vacuum. Next to the stack of tiles, a container for bond coat cement paste or thin-set adhesive is suggested.

Suppose the maximum length of an uninterrupted row to be tiled is 30 m. It means 100 tiles of 300 mm nominal length are needed, weighting in total $100 \cdot 1.5$ kg $= 150$ kg. Furthermore, 30 L cement paste or thin-set is needed for applying this row with a bonding coat of 3 mm average thickness.

Depending on the carrying capacity, two of such cartridges can be used to have more buffer, distribute the load more evenly, enable opportunities for continuous tiling, and possibilities for tiling patterns using different kind of tiles or mixing tiles from different batches.

3.5.3 Method of Drive

The full weight of the robot can be used for the placement force if the COG coincides with the line of placement. This means that part of the robot's weight is supported on the freshly laid tiles. While a riding motion on freshly laid tiles is found to be unsuitable, a short exploration on a walking tiling robot is done. About half the weight of the robot is distributed over several tiles, while it is important that each foot lands on the centre of a tile (with care) and having a uniformly distributed pressure on a tile. Only small horizontal forces are allowed on the tile, preserving it from moving. Dividing the robot's weight over multiple tiles is essential to ensure that the supporting force on one tile is lower than the placement force, even during walking.

A driving motion next to the tiles on the rough concrete is expected to be more promising. Comparing wheels or tracks, caterpillar tracks have a more stable and firm roadholding. More important, small bumps and other floor-unevenness are levelled out by the rubber profile, both in height and in riding direction.

Figure 3.4: A walking robot with centrical placement versus a riding motion with eccentrical placement.

A tracked undercarriage of Hinowa is available in several sizes and loading capacities [Hin]. OEM tracks are cheaper and have the advantage of wide and ensured availability of spares. Model PT9CG is chosen because of its loading capacity (1400 kg) and its size (1165 mm × 780 mm). See Figure 3.5, and Appendix B.4 for product information.

Figure 3.5: A tracked undercarriage from Hinowa [Hin].

3.5.4 Reciprocal Motion on Top of a Constant Moving Robot

Laying tiles is an intermitting process: tiles are placed at intervals, one after another. To prevent that cement heaps up due to a sidewards approach of tiles towards the mortar and having an askew mortar compression, it is better to have a pure downward motion during placement of a tile. The combination of this pure downward motion (thus zero motion in lateral direction) and moving to the next placement position, yields an intermittent motion for the placement head.

Repeatedly driving and stopping the large mass of the whole robot is very power inefficient. A reciprocal motion on top of the constant moving robot is suggested to create a temporary standstill of the placement head during placement. The tile's motion is in this way a superposition of a constant forward motion and a temporary backward motion.

3.5.5 Simultaneous Positioning of Tiles

For a perfectly tiled floor satisfying tolerances, tiles have to be positioned in 6 DOF with respect to the desired tiling grid, imaginarily projected on floor. Because it is chosen to tile one tile after another, all tiles on the floor will have to be positioned in 6 DOF. Instead of controlling each tile in 6 DOF apart, all tiles on the robot can be controlled to a defined position together at once. From this defined position, tiles can then be laid onto the floor. Both systems are schematically represented in Figure 3.6.

The system depicted on the left picks up a tile from the carriage and in the time prior to placement (this time interval is approximately 1 s), all 6 DOF are to be positioned in a closed-loop scheme; and kept controlled there as the heavy robot rides over the rough construction floor.

In the system depicted on the right, the whole bodywork is controlled to position. Or looking from an other point of view: The undercarriage ought to follow the rough terrain such that the heavier body, containing the buffer of tiles, is 'floating' in space and moving along the line of tiling. It has the advantage that less control action is needed in the critical time span prior to placement. Gripping and handling tiles inside the robot is such that the centre of each tile's top surface is statically determined and a simple downwards open-loop stroke is left for actual placement.

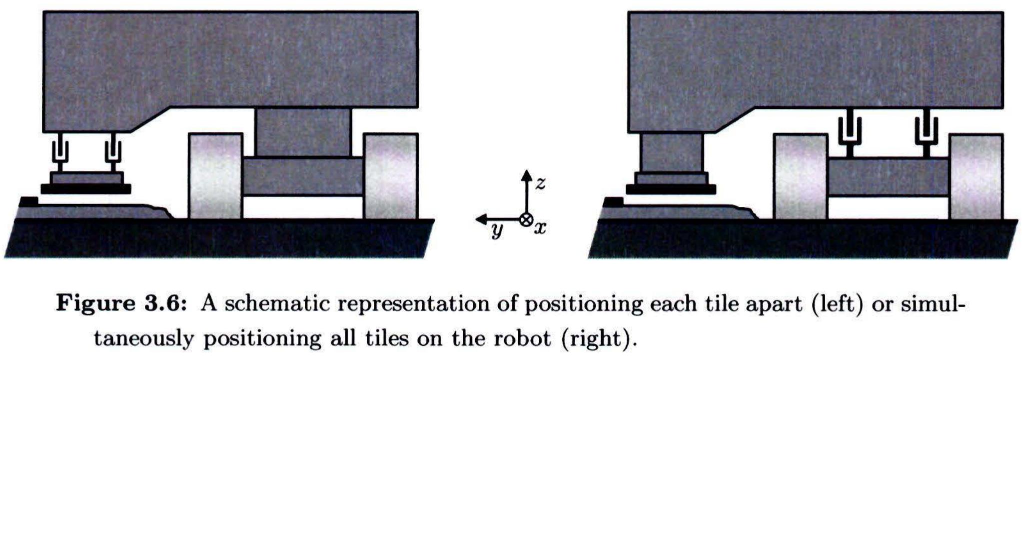


Figure 3.6: A schematic representation of positioning each tile apart (left) or simultaneously positioning all tiles on the robot (right).

Following the coordinate system assigned in Figure 1, translation z and the axis of rotation φ and ψ are controlled to be kept horizontally and at the desired height. Programming an offset enables tiling with a slight inclination for water drainage. The angular orientation in θ is controlled to stay parallel to the line of tiling and y, the position perpendicular to the line of tiling, is kept in position as well. The remaining DOF in x is the direction of tiling which aligns with the direction of the reciprocal stage. This stage can be used for positioning the tile in x.

3.5.6 Method of Power Supply

A supply of energy is essential for operation of the robot. Electric power is needed for sensorial technique and robot control. The undercarriage comes standard with a hydraulic motor but can probably be exchanged with an electric drive if no other hydraulic components will be used in the design. Vacuum will be used for gripping the tiles and this can be generated by a vacuum pump or a venturi valve using compressed air.

Electric energy can be fed to the robot by a long cable from the main power. However, the robot can experience troubles with the power cable while manoeuvring. Tilers and robot operators should pay attention to the cables and avoid driving over them as much as possible.

In comparison to this, power supply from an internal combustion engine, makes the robot more mobile, and even able to operate where no main power connection is available. A small internal combustion engine with coupled generator is commercial available and commonly applied to similar systems. The drawback of such systems is the emission of pollutant exhaust gases. Its use is limited to open or semi-open, well ventilated areas.

Third option is feeding the robot with electric energy from batteries. Though there are commercially available systems (e.g. from hybrid car technology); batteries have limited life, are heavy and expensive. An electric power cable connection can easily be laid for backup in case of a empty battery.

Making a choice on the way of energy supply is left to the preferences of the customer. If emission of exhaust gasses is unacceptable, an electric version with batteries can be chosen. The possibility for using a main power cable is a simple and inexpensive add on.

3.5.7 Usage, Cleaning and Maintenance

The tiling robot and also the mortar robot, will make their way to a rather rough environment and will face extensive use. There will be a long-term exposure to vibrations and also the robots will face outdoor weather conditions. The robots will be (co)operated by construction workers, who are, in general, not used to handle fragile equipment.

The handling of cement, sand and water (especially the combination of those) requires special attention to the design of the robots. Without proper protection, moving parts such as bearings, guides or driving parts will show excessive wear.

While sand inside construction elements immediately causes destructive behaviour, it still is easy to seal and collect because it consist of relative large and heavy particles. Unlike sand, dry cement powder is light and while handling, it easily produces clouds of cement dust blown into the air. It can enter sensitive elements even through smallest gaps in seals and will cause wear in the long term. In combination with water, moist or even a humid environment, this cement will stick to the robot. Once hardened, it can cause malfunction or seize up of the robot.

Proper sealing of moving parts requires attention. Next to that, wear-prone parts have to be easily replaceable. All parts concerning the handling of wet cement and fresh mortar (but desirably the whole machine) have to be cleanable with a pressure washer.

3.5.8 Choice of Materials

The presence of cement to the robots has some metallurgic aspects and influences the choice of construction materials. Cement submerged in water forms a very alkalic electrolyte and sets stage for electrochemical and galvanic corrosion.

It restricts the use of aluminium as construction material. Firstly, as a positive, aluminium of its own is resistant to corrosive environments because it develops a thin oxide layer which acts as a protective coating. Alkalis in concrete (mainly Na_2O) may dissolve the oxide coating but normally new barriers of hydrated alumina tend to form immediately. Extensive corrosion however occurs with a galvanic connection between dissimilar metals (e.g. aluminium and steel) and a conductive electrolyte consisting of water or a calcium hydroxide ($Ca(OH)_2$) solution. As aluminium has a lower electrochemical potential than iron, it will corrode.

Galvanic corrosion is to be eliminated by avoiding dissimilar metals, or by a proper galvanic isolation of the metals, e.g. using plastic separators. The electrochemical corrosion can be used in an advantageous way: Blanc steel gets a protective galvanic coating of for example zinc, which acts as a corrosion buffer.

Parts which are in direct contact to water or fresh cement are to be made of stainless steel because of the best resistance to the cement corrosive effects. Still it is susceptible to pitting corrosion, stress corrosion cracking and crevice corrosion.

3.6 Design Choices Made

In this chapter, various aspects on the tiling robot are considered. From this, several design choices are made. These are summarised below.

- To be cost-effective within the estimated cost price, one tile per 2 seconds should be placed by the tiling robot during tiling mode.
- Tiles may have large dimensional variations. For achieving a 'superbly' tiled floor, tile placement inaccuracies are derived for 6 DOF, and dually specified with respect to adjoining tiles and to the overall tiling grid.

- It is experienced that tiles can be placed with a static force on a cement paste bond coat. A force of 0.4 kN already gives a reasonable tile embedment. A force of 1.5 kN can be regarded as the maximum design force.
- It is chosen to prepare a perfectly flat and compacted mortar bed and install a tile on the desired position. The cement paste bond coat fills the gab and should accommodate tile and mortar bed tolerances.
- Tiles should not be installed in sets simultaneously, to avoid regular patterns in the finished floor.
- The use of cartridges for tiles and bond coat cement paste is suggested for easy recharging and transporting by fork-lift truck.
- From a constantly moving robot with rubber tracks, tiles are placed with a temporarily backward motion.
- All tiles are positioned simultaneously on an actively controlled suspended body.
- Power can be supplied by an internal combustion engine, or electrically by batteries and main power connection.
- Important issues on the robot's design are robustness, protection against water and cement dust, replaceability of wear-prone parts and corrosion.

Chapter 4

Mortar Robot Design Aspects

This chapter treats several design aspects of the mortar robot. Different stages of mortar handling are examined: Delivery and transportation of mortar to the construction site, mixing and buffering, applying mortar on the floor and compacting it, and finally, the scrape off of the mortar bed at the desired height. The chapter is concluded with a schematic design of the mortar processing line on the robot.

4.1 Delivery and Transportation of Mortar

Prescribing a desired speed of tiling, requires a sufficient supply of mortar to keep up with tiling. Assume placing one 300 mm tile every two seconds on an average mortar bed thickness of 4 cm: A mortar flow of 6.5 m^3/h is required. The actual demand of mortar changes with varying bed thickness. Taking into account idle time spent on manoeuvring, refilling and repositioning the robot, the average demand of mortar will be lower.

The use of existing procedures and equipment for the delivery and mixing of mortar is advantageous. It helps to lower the cost and increases acceptance by tilers. Due to the large flow of mortar, traditional mixing in a portable concrete mixer is not suitable.

The consistency and workability of mortar used for ceramic flooring is about the same as used for screeding. Screed conveying equipment (Figure 4.1a) uses compressed air to pump freshly mixed screed mortar from the construction site to the floor area. Dry components (sand and cement) are mixed with water in a mixing vessel of typically 200 L. After some minutes of mixing, compressed air is applied to transport the mixture through a delivery hose. Appendix B.2 gives a more detailed description on possible mortar delivery equipment.

Loading the mixing vessel (shovelling sand and lugging cement bags) is a heavy job. Delivery, mixing and conveying is combined in the Trans-Mix. This is a semi-trailer truck with separated compartments for dry sand and cement; at the back equipped with the same mixing vessel and pump (Figure 4.1b).

Instead of pumping, the next option being considered is conveying mortar by a fork-lift truck. Ready mixed mortar can be delivered by a mixing truck (Figure 4.1c) to the construction

(a) Compressed air conveyor

(b) Trans-Mix semi-trailer

(c) Concrete mixing truck

(d) Silo with fork-lift truck

Figure 4.1: Ways of mixing and transporting mortar.

site, but this is not preferable. It requires a batch of mortar (about 10 m^3) to stay fresh for at least 2 hours. A retarder can be added but this also slows down the curing of the floor.

Instead of ready mixed mortar, a dry sand-cement mixture is brought to the construction site in large silos (capacity up to 22 m^3). A mixer is installed at the bottom (mixing rate up to 6 m^3/h) (Figure 4.1d). Instantly, fresh mortar is made with the addition of water. Instead of pumping the mortar towards the mortar robot, a fork-lift truck is used.

The method of pumping is ideal when the delivery hose is permanently coupled to the robot or recurrently during refilling. With the latter, a 13 metres long strip of mortar can be laid from a 200 L batch (with a compaction factor of 80%).

The delivery hoses being used are rather stiff and inflexible. When connected to the robot, disturbance forces caused by the repetitive pumping of clods of mortar, will influence the positioning accuracy and driving trajectory. Hoses laying on the floor make it difficult to drive around with both robots simultaneously, as well as for the lifting truck transporting tiles. They have to wait for one another to pass by and machine operators must pay attention to keep the hoses straight.

Driving around a fork-lift truck is not the most efficient way of transporting mortar in only one direction from the mixer to the robot. Because a fork-lift truck is brought into action on the building site for transporting tiles though, it is chosen to utilise it for the mortar too.

Not only mortar is needed to run the mortar machine; also components for the render coat have to be on the mortar robot and need refilling periodically. It is easier to host all components in one cartridge than to have multiple hoses and pumping equipment.

4.2 Buffer of Mortar

The suggested cartridge or mortar container contains all mortar to lay a continuous strip of mortar on the floor. The length of this strip is related to the total weight limit of the robot.

For the sake of a uniform design, the same undercarriage is selected for the mortar robot as used for the tiling robot. Subtracting from the total weight limit of 1400 kg the undercarriage mass of 250 kg and an estimated mass of 300 kg for the body construction yields a loading capacity of about 700 kg for mortar. Having an average bed thickness of 4 cm and assuming a compacted mortar density of 1800 kg/m^3, yields a continuous strip length of 32 m. However, not all strips require the same amount of mortar and not all mortar will be used, but floor length (or width) up to 30 m can be tiled continuously.

The time needed for mixing the mortar and refilling the container lies in the same order as the time needed for tiling one row. Two containers are then required, where one is put on the robot and the other is on the mortar preparation site. If the mixing time is found to be too short, or to create a larger buffer of mixed mortar, a third container can be included in the process. This creates a cyclic process with three parallel stages, namely refilling the container, additional mixing and consuming the mortar on the robot.

4.2.1 Design of the Buffer Container

The container should be able to carry 700 kg of mortar. With an estimated density of 1450 kg/m^3 for uncompacted mortar, it occupies a volume of 0.5 m^3. Next to this, a smaller compartment is reserved for the render coat, consisting of either separated or mixed water and cement powder.

As fresh mortar has an earth-dry consistency, it does not easily drain off. This should be taken into account when designing the container. The bottom should be steep and a worm shaft can be placed to push the mortar out of the container. Counter-rotating the worm is then used for additional mixing the mortar in the container. Similar to concrete in a mixing truck, the curing process of cement slows down when mortar is in movement.

While the worm shaft might be incorporated in the container design, its drive is preferably external so that the container can be fully made of stainless steel and be cleanable with a pressure cleaner.

4.3 Application of Render Coat

Prior to laying a strip of mortar, a coat for bonding must be applied to the concrete floor. Its components are buffered in the container. For applying it to the floor, standard sprinkling equipment from the agricultural or food processing industries, might be adopted.

For a good adhesion of water with the floor and to let dry cement dissolve in water, the render coat is traditionally spread and wiped out with a broom. A similar broom might be needed for automated applying of the render coat, or possibly a premixed slurry can be sprayed on the floor with pressure, without sweeping it. Further experimental research is recommended on the method of render coat apply and its mechanical appliance.

4.4 Application of Mortar

4.4.1 Design Aspects

Laying a strip of mortar is actually extending the prior laid mortar strip (except for the first strip laid). It is important that both strips cohere without the inclusion of air. Otherwise, the discontinuous mortar bed is less able to average internal stresses, for example caused by uneven thermal expansion or the natural shrinkage of curing cement. It leads to high local stresses in the tile, which may end up in a cracked tile. A gradual weld of the two mortar strips will decrease this effect. For a good bonding, some render coat can be applied on the mortar joint surface as well.

Next to a horizontal focus on homogeneity, also the degree of compaction in vertical direction should be of equal order. If the floor has an uneven load-bearing capacity, a tile may crack as well when heavily loaded.

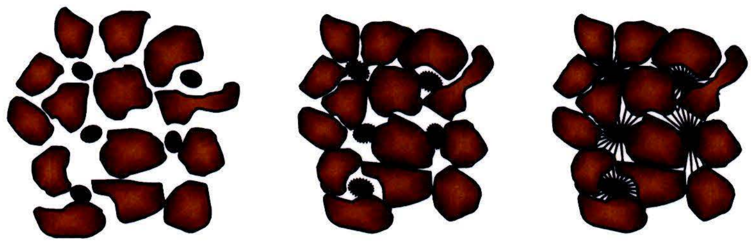
Mortar is put on the floor and spread to form a homogenous cross section of mortar, thicker than the desired bed height. Next, the mortar is compacted by pressing or vibrating it together. The necessary compaction of mortar needs some more attention as it is an important factor in the final floor properties and influences the machine design.

4.4.2 Compaction of Mortar

As stated earlier, mechanised impulse fixation of tiles induces (unpredictable) vibrations in the tiling robot, which is not desired. The same holds for mechanised impulse compacting of mortar, influencing the positioning measurement and machine condition. Other methods for compaction are to be considered.

Though the final strength of the floor may be ascribed to cured cement, it can be enhanced by rearranging the sand particles to a denser settlement. The latter increases the load-bearing capacity and less cement is needed for the same strength. Figure 4.2 gives a representation of the processes of compaction of particles and hydration of cement.

A key process in compacting mortar is to overcome the internal friction between particles to let particles rearrange. Less compaction effort is needed when the structure is slightly moist.



(a) Loose structure (b) Dense structure (c) Cured structure

Figure 4.2: Composite mortar structures.

Moisture acts as a lubricant, yet too much water yields a less compacted structure as water now fills the voids. Earth-dry consistency is an ideal moisture level for the compaction of granular materials.

Mechanical compaction techniques are found in various fields of construction. For example, soil is compacted for improved load support. Vibrating pokers and beams are used to eliminate most of the unwanted air pockets in freshly laid concrete slabs. Due to the dry and stiff consistency of mortar (unlike more liquid concrete), soil compaction techniques are more appropriate to be considered for mortar compaction.

Four types of soil compaction effort are distinguishable: deadweight pressure, kneading (such as rolling), impact and vibration. The first two are assigned to the group of static forces and the latter two to vibratory forces.

From the basics of soil mechanics, static compaction increases the density of the upper layer of a soil bed, but is limited to reach any appreciable depth. Though a mortar bed is relatively thin, the mentioned effect is experienced in practical tests (Figure 4.3). Deadweight pressure of 40 kPa is applied to a 4 cm thick bed. Only the top layer is found to be compacted. Rolling the bed in combination with a downward force gives a much better compaction, but as discussed in Appendix A.1.5, it still may not give the desired level of compaction.

(a) Compaction by static pressure (b) Compaction by rolling (c) Compaction by slapping

Figure 4.3: Static and impact effort applied to a mortar bed during experiments.

Vibratory compaction utilises a mechanism to create downward peak forces in addition to static weight. The pulse forces move through the mortar layer, setting particles in motion and moving them closer together for the highest density possible.

Compaction by impact is a proven method as it is applied at manual compaction. Yet, it is likely that compaction of the mortar bed by vibration may result in a similar or even higher density; or to put it another way, less compaction effort is needed to achieve the same level of compaction.

For a concrete structure, the increase in compressive strength through vibrated compaction rather than attained by hand punning, is illustrated in Figure 4.4 (reproduced from [Orc73]). The examined concrete mix has a 5:1 sand/cement ratio and varying water/cement ratios.

It shows that the compressive strength is limited when compacting the concrete structure by hand. An increased compressive strength can be obtained by vibrating a dry mixture. However, to achieve this, the time of vibration also has been increased.

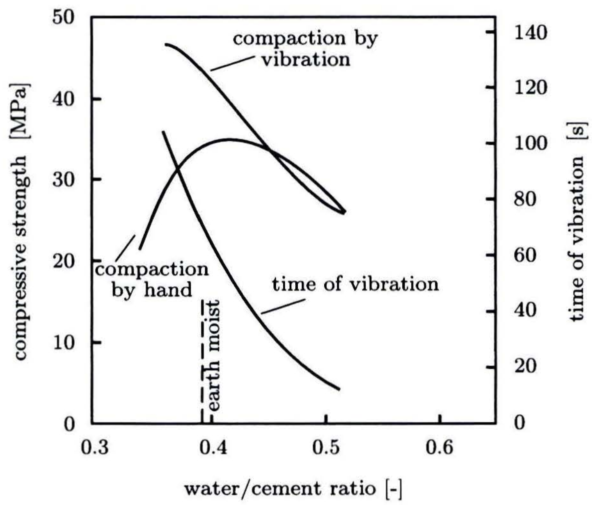


Figure 4.4: Increase of strength obtained by vibrating a 5:1 sand/cement mix [Orc73].

Compaction by vibration is a common method for sand compaction in road construction. Two examples of sand compaction equipment are shown in Figure 4.5: a vibratory roller and a vibratory plate.

Figure 4.5: Vibratory equipment used for sand compaction.

Vibrational compacting is not experimentally tested on a mortar bed. Further testing on the method and design of compacting equipment is recommended. Frequency, amplitude, static pressure and duration of vibration are important parameters when designing and tuning vibratory equipment.

4.4.3 Scrape Off at Correct Height

The last step in preparing a mortar bed is scraping off the compacted strip to the desired height.

A simple way of scraping is by penetrating a metal wedge or blade through the mortar bed with a forward motion. The shape of the wedge or blade and its cutting angle are of major influence on its performance. Literature on agricultural plow design (such as [KKu83]) as well as experimental testing helps on designing the scraper.

It is important that the scraper leaves a flat bed of untouched mortar. Figure 4.6 shows some examples of open crack formation which affect the mortar bed finish. The formation of open cracks is studied in agricultural soil mechanics.

A smooth finish can be guaranteed with a proper scraper design and adjustment. The temporary application of pressure on the bed at the intake of the scraper might prevent open crack formation. Furthermore, instead of cutting mortar, the blade can be subjected to an in-plane oscillation, such that a sawing motion is obtained.

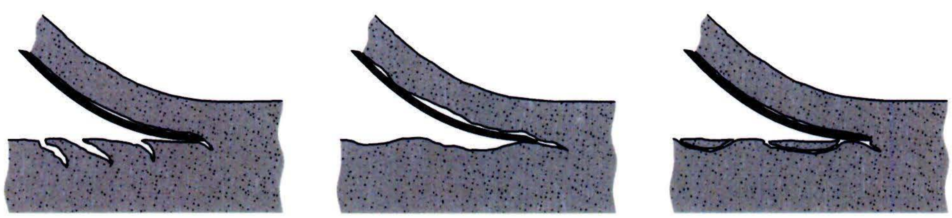


Figure 4.6: Formation of tongues, holes and slices during intake with open crack formation. [KKu83]

The excess of mortar is to be lead away from the levelled bed. It could be dropped next to the bed on the floor if render coat has already been applied there. It is better taken away from the bed and returned to the mortar buffer for reuse.

4.5 Arrangement of Mortar Processing Components

The following arrangement of components for mortar bed preparation is concluded:

Dry sand and cement is delivered to the construction site in a silo or semi-trailer. Water and cement, or a premixed slurry, is loaded on the robot for applying a render coat by sprinkling and wiping out. A buffer container on the robot is exchangeable and can be refilled with mixed mortar using a fork-lift truck. Section 3.4 reasoned to prepare a flat and fully compacted bed of mortar. Vibration yields a high degree of compaction. A vibratory roller is taken for an initial conceptual design. Finally, the laid mortar is scraped off to obtain a flat bed with tile placement φ,ψ,z-precision.

The mortar laying process, as suggested above, is a continuous process. It means that all particular mortar processing devices are assembled after each other on the mortar robot. Figure 4.7 shows a schematic conceptual design of all components on the robot. Because of the line processing character, the robot can only lay a strip of mortar in one direction, that is from right to left in Figure 4.7.

It further means that a mortar strip of the length of the robot plus the length of the processing line, cannot be laid by the robot. The remaining tileable length is illustrated in Figure 4.8. Here, it is assumed that part of the render coat which cannot be laid by the robot, is manually applied. Note that, with the robot design of Figure 4.7, the render coat device has to be lifted before driving back.

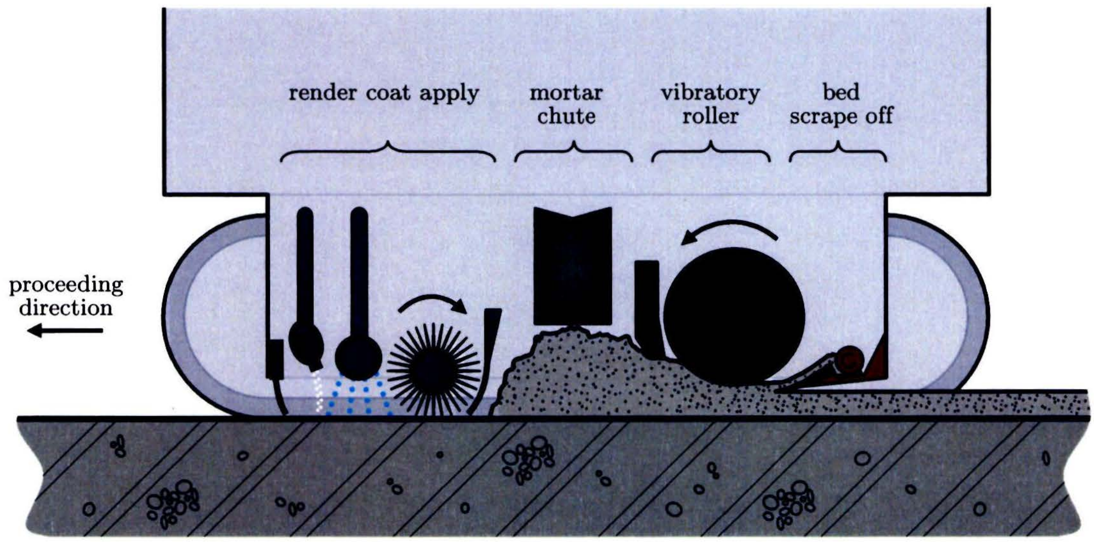


Figure 4.7: A schematic conceptual design of the mortar-laying process line.

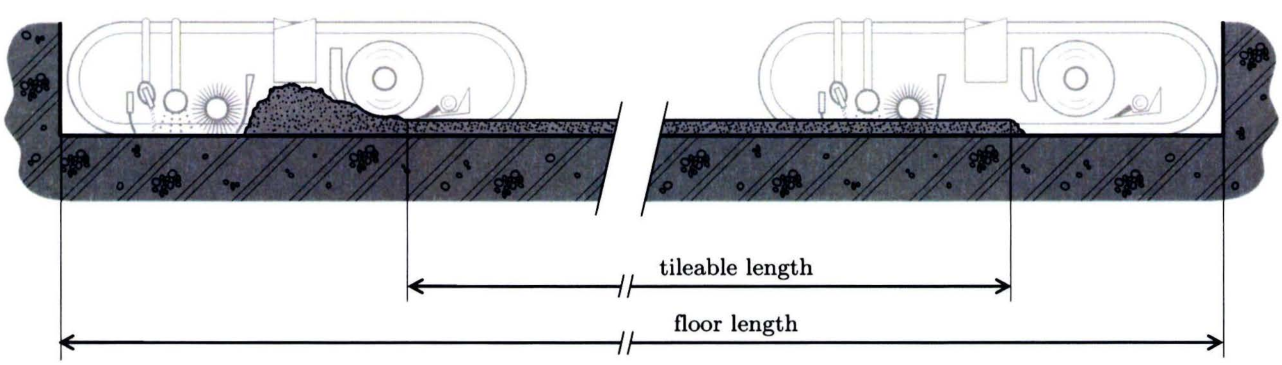


Figure 4.8: Part of the floor length cannot be covered with a finished strip of mortar.

Chapter 5

Measurement System

Section 3.2.3 elaborated on the placement accuracy of tiles that has to be achieved. It resulted in guidelines for the maximum permissible placement error, specified in 6 DOF (Table 3.4).

Following from the way floor quality is specified, a division in placement inaccuracy is made according to the reference of measurement. One can refer in absolute sense to an overall tiling grid, imaginarily projected over the floor area, or in relative sense to adjacent tiles.

As 'referring to' is something different than 'measuring to', a measurement system with sufficient precision is required to be able to achieve the desired placement accuracy.

Table 3.3 reveals that variations in the tiles' dimensions can be large. Length and width variations are to be smoothed away in the tile joints. For an equal division over the four surrounding joint spaces, the tiles' geometric centres are considered when aligning tiles. See Figure 5.1.

Like the geometric centre is considered for x,y,θ, the average level of the tile's top surface is considered for φ,ψ,z. Variations in thickness and flatness are to be smoothed away in the bond coat underneath the tile.

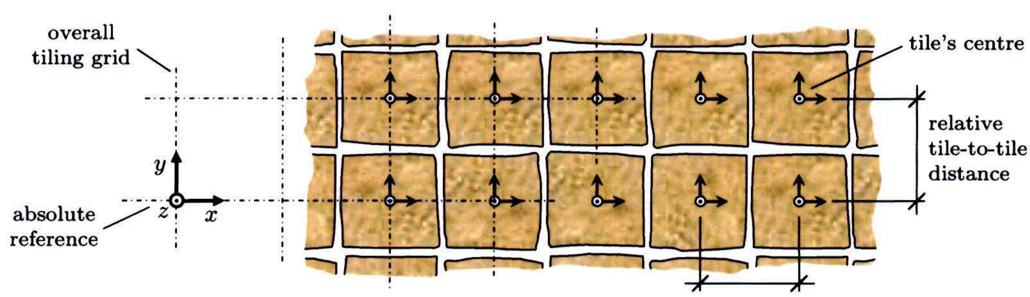


Figure 5.1: The geometric centres of tiles are considered. Measurements can be either in relative sense to adjacent tiles or with respect to an overall tiling grid. Dimensional variations are smoothed away in the joint spaces.

Regarding the measurement of tiles, consider the following propositions:

- A perfectly aligned floor can be laid when measuring to previous laid tiles with zero inaccuracy.
- A perfectly aligned floor can be laid when measuring to the overall imaginary tiling grid with zero inaccuracy.

In reality, zero inaccuracy can never be achieved because of inevitable uncertainties in measurements. Yet, as long as those uncertainties stay within the defined placement inaccuracies, 'perfect' tilework is sufficiently approached.

In line with the above-mentioned hypothetical situations, it is possible to measure with respect to only one reference, and still satisfying to the dual defined tile placement inaccuracies, in the following two cases:

- A measurement system is utilised, measuring tile-to-tile distances with such small x, y-inaccuracy that the cumulative error over the full length of the floor, is smaller than ± 4.4 mm.
- A measurement system is utilised, measuring with respect to the overall tiling grid, and capable of achieving x, y-inaccuracy smaller than ± 0.9 mm over the full length of the floor (set to 30 m).

If the above mentioned systems are found not to be achievable, a third option is a dual measurement system consisting of an absolute measurement system with x, y-inaccuracy $< \pm 4.4$ mm and a tile-to-tile measurement system with x, y-inaccuracy $< \pm 0.9$ mm.

Next to the mentioned x and y values, also z, θ, φ and ψ inaccuracies are to be considered in a similar manner.

In the next two sections, applicable sensors and corresponding techniques will be investigated for relative and absolute measurement, respectively. Section 5.3 will examine the options and conclude on using relative or absolute measurement, or that a redundant system in the sense of a combination of both is unavoidable.

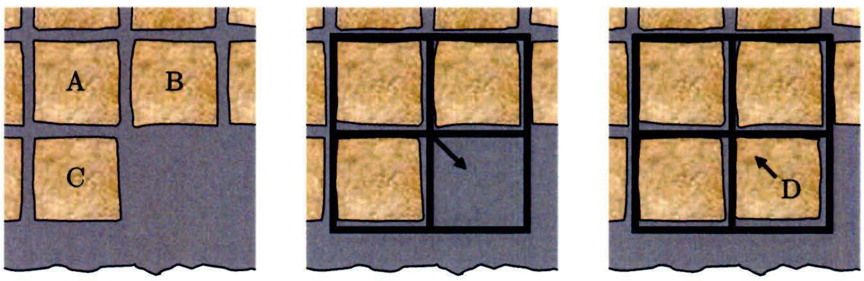
5.1 Sensors and Devices for Relative Measurement

This section discusses two measurement systems which can be classified to relative measurement. This means that tiles are positioned with respect to adjacent tiles and not referred to an absolute grid.

Note that laying tiles while only measuring relatively, the first row and first column of tiles is required to be set manually and be guidelines for the robot. This should be done very precisely as the quality of the whole floor relies on those reference tiles. Another possibility can be to set up a laser on the floor which projects a cross on the floor, acting as homing reference for the robot. Such a laser setup is discussed in Section 5.2.2.

5.1.1 Frame for Tile Alignment

A concept of mechanically aligning to adjacent tiles is described in this section. Surrounding tiles are sensed and taken as a reference for the tile to be placed. This is performed using an alignment frame, indicated in red in Figure 5.2. It is placed temporarily over installed tiles A,B,C such that the frame takes over the position of those tiles. A new tile D can now be placed using the frame as a reference.



1. Three installed tiles are used as reference. 2. The frame is placed, touching the tiles. 3. A new tile is placed, guided by the frame.

Figure 5.2: An alignment frame is put temporarily over installed tiles and is a guide for installing a new tile. Tiles are depicted with an exaggerated non-straight edge.

Figure 5.2 illustrates this concept for a reduced situation in the horizontal x,y,θ-plane. In a similar way, the frame is laid on the tiles such that is forms a φ,ψ,z-reference. The new tile is placed on height such that it continues the tiled surface.

Thin strips mounted on the frame are lowered into the tile joints such that it can detect the tiles' x,y,θ-positions. To minimise joint width, the strips on the frame ought to be thin, but this makes the frame fragile. High-graded steel enhances the fragility, but it also increases the risk of damaging the tiles. The alignment frame is required to be handled with care.

The dimensions of the frame should be such that slightly bigger tiles fit in the frame as well. When designing or adjusting the frame, one should take account of the tiles' dimensional tolerances (as determined in Table 3.3). Because the minimal achievable joint width is resulting from the tiles' dimensional tolerances plus strip thickness, the nominal joint width will have to be larger with this method of installation.

The alignment frame is only meant to determine positions. It is important that no excessive forces will act on the already installed tiles or they might shift. Likewise, when installing a tile, no parasitic lateral forces may be acting on the frame. It may only be used as a positioning guide.

Because all tiles are aligned within one corner, all tiles in principle have a miss-alignment of half the tile's dimensional variation with respect to the imaginary tiling grid. There is not much tolerance left for variations in placement. An equally closing clamp can be used to define and align to the tile's geometric centre; yet this makes the frame even more fragile and much more complex.

5.1.2 Camera-based Computer Vision

In contradiction to a touching frame, contact-less sensing with respect to previous laid tiles is possible using computer vision. In literature, computer vision is repeatedly discussed as a technique for handling and aligning tiles ([ASW96], [Kah04], [Nav00]). The placement of tiles is observed by cameras. Information on the tiles' positions can be obtained after processing the data of the taken images.

[ASW96] showes two examples of tile images and their processed images for a high contrast tile and a rough reflective tile (Figure 5.3). In the latter, reflections and prints and the fact that the tiles are packed together, cause troubles in determining the tiles' edges.

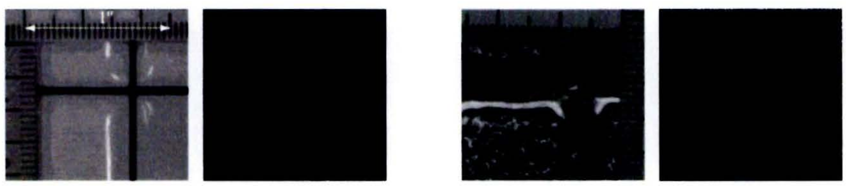


Figure 5.3: Two tile images and their processed outcome. [ASW96]

The latter method only considers in-plane positions. To detect also out-of-plane positions and height variations, line projection from an oblique laser is a commonly used method; see Figure 5.4.

A laser diode beams a line from an angle on two tiles with a joint in between. A camera observes the tiles from a perpendicular orientation. A discontinuity in the projected laser line, reveals the location of a joint. The joint width can be determined from the number of indented pixels.

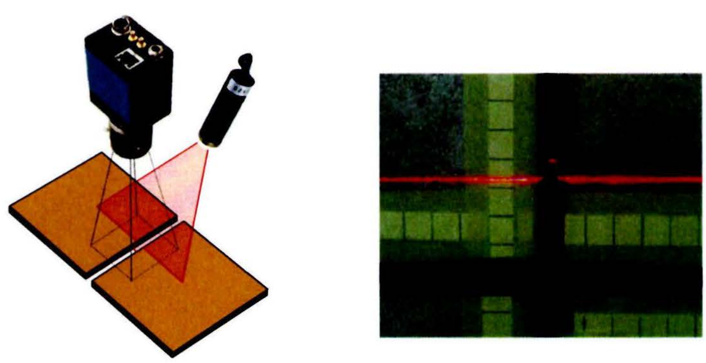


Figure 5.4: An oblique laser beams a line on the tiles and a perpendicular placed camera can detect the joint.

Figure 5.5 shows an example of how a clear image can be obtained, having less influence of background texture and bad lighting conditions. Two images are captured immediately after each other, successively with and without the projection of a laser line. Subtracting the two images from each other, results in a simple image where the projected laser line is clearly visible. This simple image allows a fast collection of relevant distances.

Figure 5.5: An image with projected laser beam is subtracted with an image without. [Kah04]

[Kah04] elaborates on the positioning of tiles with the above described technique and suggests the use of five laser lines in a configuration as shown in Figure 5.6. Positioning a tile in x and y is suggested to do by making the joint widths at line 3 and 4 equal to that at line 1 and 2, respectively. The orientation of the tile in θ is determined likewise using laser line 3 and 5. The height of the tile in z is determined from the degree of collinearity of the two segments of line 3, 4 or 5. The tilt of the tile in φ and ψ can be determined from the parallelism of two broken line segments.

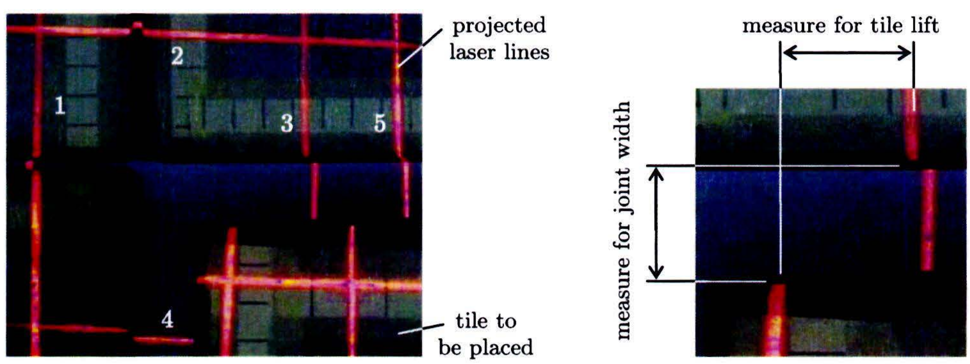


Figure 5.6: Five laser lines are used to position a tile with respect to three adjacent tiles. [Kah04]

Experiments with the depicted setup revealed that the angular correction error in θ was large. Yet, on account of this, putting the lines 3 and 5 further apart, requires a broader view of the camera and decreases measurement resolution. Observing a 5 cm square with a 1000 pixel sensor yields a sensitivity of 0.05 mm/pixel. In general, having more pixels increases processing time and effort.

The above described system observes tile corners. Similar to the solution with an alignment frame, dimensional variations are not equally divided over the four adjacent tile joints but (in terms of Figure 5.6) assigned to the lower right corner. However, in the next row to be tiled this lower right corner will become the upper left corner: Cumulative errors will increase over the whole floor.

Instead of aligning to the tile's corner, its geometric centre should be considered. One option is to measure all tiles on the robot before they are placed. The tile's distances from corner to centre are stored in a database, corresponding with the floor pattern. When placing a tile, the camera image is compared with the location of the adjacent tiles' centres, looked up from the database.

Another option for determining the geometric centre of installed tiles is by temporarily marking the tiles. A less obvious mark can be made by dispensing small droplet of UV-readable ink. These small dots on the tiles are washed away during the grouting process by grout cleaners (Appendix B.3.2). The marks are not visible to the naked eye, but when illuminated with ultraviolet light, they turn visible and the fluorescing dots can be observed with image sensors.

The extra operational costs are very low as presumably hundred thousands of small dots can be printed with one litre of ink. UV-ink or UV-powder suspended in water costs no more than € 100 per litre (Figure 5.7).

Figure 5.7: Some examples of UV-readable ink and powder.

The time needed for the sequence of taking an image, processing it and making decisions, typically lies in the order of 10 to 100 ms, provided that a modern computer processing unit is used. Many systems have their measurement update rate limited by a camera frame rate of 30 Hz and perform parallel image processing.

Because the processing time can be relatively long, it is more suitable to incorporate computer vision in a sense-plan-act robot control methodology, rather than high-bandwidth closed-loop position control.

Sense-plan-act control means in terms of tile placement, that a tile to be installed together with adjacent tiles is sensed by taking an image. Image data is processed and a strategy is planned. Finally, the planned correction is performed, after which the full cycle starts again to bring the tile into its desired position, iteratively.

5.2 Sensors and Devices for Absolute Measurement

This section focusses on systems that measure with respect to a single reference. It means that all tiles on the floor are aligned to the overall imaginary tiling grid by absolute measurements to the subjected reference(s).

An inclinometre is examined for φ,ψ-measurement. Next, various laser systems are investigated. Finally, a sophisticated system of active beacons is described.

5.2.1 Inclinometre Sensor for φ,ψ-Measurement

An inclinometre is an instrument which measures the tilting angle with respect to the vector of gravity. A dual-axis inclinometre has two accelerometre sensors placed perpendicular. It is a small and relative cheap tilt sensor. Accuracies can be achieved in the order of 1° to 0.01°, depending on the sensor characteristics and environmental situations.

An example of an inclinometre is the SST750 [SVT], with a resolution of 0.001°. Its absolute measuring accuracy is better than ± 0.01° at 25 °C operating temperature. The response time is 0.1 s with an update rate of 25 Hz. A picture is shown in Figure 5.8.

The sensor box is to be mounted on the robot's body to provide feedback on its tilting angles φ and ψ.

Figure 5.8: The inclinometre SST750 [SVT].

5.2.2 Various Laser Systems

A laser system produces a straight and stable, focusable monochromatic beam of light which can be utilised to perform measurements. Laser systems offer high accuracies over a large range.

The functioning of a laser measurement system requires that the beam may not be blocked by tilers walking around, the robots themselves, or any other objects on the floor. Swirling dust and moisture may also obstruct the laser beam or forestall an accurate measurement.

Multi-Line Laser

A fast rotating laser beam projects lines on the wall or floor. Its plane in space can be used as a reference for the robots. Such laser systems are commercially available and already commonly used in construction.

A rotating line laser, set up horizontally, can be sensed by a robot and used as a height reference over the full floor. Other systems have also the function of projecting vertical planes, to be used as a home reference for the robot and be a guide when aligning other measurement systems.

The installation of the multi-beam laser (on a tripod or wall mount) is the first step in tiling a floor. This step requires attention as it has big influence on the final floor quality and the amount of mortar to be used.

Figure 5.9: Multi-line laser PCL 8 P RX with receiver RX 51 from Laserliner [ULL].

Figure 5.9 shows a picture of the PrecisionCross-Laser 8 RX from Laserliner [ULL]. It has four horizontal laser diodes, producing a 360° laser line, and four others emitting vertical planes.

The PCL 8 P RX laser has a self-levelling range of ± 4° with an accuracy of 1 mm per 10 m, and an automated horizontal tilt alignment. Laser receiver RX 51 can detect the laser lines up to 50 m radius in any ambient lighting condition. The laser is splash water and dust protected (class IP54) and comes with a carrying case for safe transportation.

Spot Laser

A spot laser produces a single straight beam. This can be used as a guide for the robots while tiling a row. An example of such an adjustable spot laser is shown in Figure 5.10: The Revolution Red 310S from Laserliner.

Like the PCL 8 P RX, it has an automatic alignment by positioning motors and temperature-stable sensors to a precision of 1 mm per 10 m. Furthermore, it has an anti-drift system by continuous monitoring the alignment of the laser. It is dust and splash water-proof (class IP66).

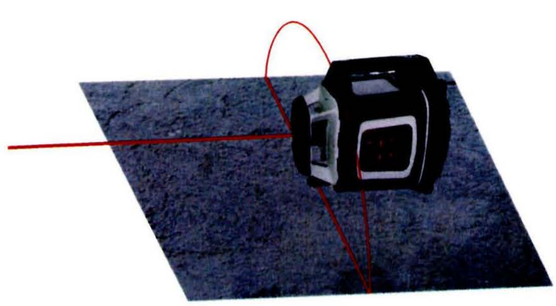


Figure 5.10: Flat installation of the Revolution Red 310S, emitting a straight and a rotating laser beam [ULL]

The laser beam can be sensed by the robot using a position-sensitive detector or PSD (Figure 5.11). For a basic PSD, an incident laser spot causes a local change in resistance on a photoelectric layer and allows electron flow. By sensing four electrodes, the y,z-position of the spot on the sensor can be determined. Modern detectors also use CMOS or CCD image sensors.

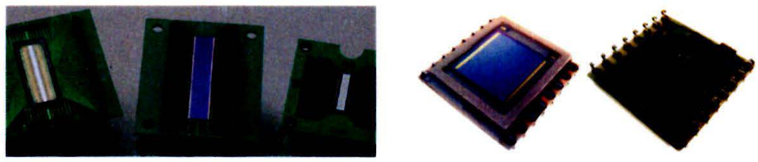


Figure 5.11: Some examples of 1D and 2D position-sensitive devices with signal processing electronics.

Laser Distance Sensor

Lasers can also be used to perform absolute distance measurements. At such systems, a transmitted pulsated laser beam is compared with its backscattered beam.

The accuracy that can be achieved is strongly correlated to the measurement range of the sensor. One of the most accurate sensors is the Dimetix FLS-C10 (Figure 5.12, [Dim]). It has a typical measuring accuracy of ± 1.0 mm and ± 0.4 mm repeatability. The specified maximum measuring rate for the FLS-C10 is up to 25 Hz in tracking mode. The measuring range is on natural surfaces 0.05 to 65 m but can range up to 500 m on reflective targets. With protection class IP65, it can be safely mounted on the robot, providing positioning information in x-direction.

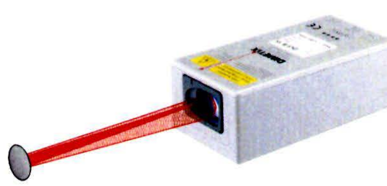


Figure 5.12: Dimetix FLS-C10 laser distance sensor [Dim].

5.2.3 Active Beacon System

The use of GPS for robot localisation would be very favourable; however its positioning accuracy and measurement rates are limited. GPS in combination with ground base stations and real-time kinematic (RTK) surveying will provide up to centimetre-level accuracy, which is not sufficient for accurate tiling. Moreover, GPS may have bad indoor performance due to loss of satellite signals.

Similar to GPS, one can set out a number of local 'satellites' in the room to be tiled, known as active beacons. Trilateration and triangulation methods are used to compute the robot's position and orientation with respect to the beacons.

The method of trilateration is based on distance measurements between the usually stationary transmitters and the on-board receiver, using time-of-flight information. This principle is used in GPS. Triangulation is based on angular measurement. Such a system typically has a rotating sensor on-board which registers the angles to the transmitters, relative to the robot's angular orientation.

A commercial active beacon system that matches the range and accuracy requirements is iGPS, developed by Metris (currently Nixon Metrology [NiM]); see Figure 5.13. Multiple transmitters are placed as beacons, having a rotating laser. A receiver on the robot detects the laser pulses and calculates the robot's position.

Figure 5.13: iGPS transmitter and sensor system and some applications. [Mau09]

According to the manufacturer, the sensor has a receiving range from 2 m up to 80 m and inaccuracies of < ± 0.1 mm for 3D-position can be achieved. [MüS09] elaborates on the working principle of iGPS and validates its performance with practical tests.

Though the system uses angular measurement, it does not work with the triangulation principle. The transmitters have two rotating fan-shaped laser beams at an angle of 90° from each other. The two 'fan blades' both have an opposite inclination from the vertical of ± 30° (Figure 5.14). The altitudinal angle between the transmitter and sensor is calculated from the time interval between the two laser beams. To derive the azimuthal angle, the sensor makes use of infrared reference pulse, sent out omnidirectionally by the transmitter, every other rotation.

In principle, one receiver needs only two beacons for computing its x, y, z-coordinates (Figure 5.14). In practice, typically four transmitters are used to increase accuracy and to cope with obstructed transmitters.

The sensor consists of a ring of photo-sensitive diodes to detect the laser beams and infrared reference pulses. One sensor is able to determine x, y, z-positions. Mounting three sensors, all 6 DOF can be computed by a processing unit on the robot.

iGPS is developed and mainly applied for static measurement applications, for example coordinate measurement of large ships and aeroplanes. Inaccuracies of < ± 0.1 mm are validated by [MüS09] for static measurements. Furthermore, because of the 40 Hz rotational frequency of a transmitter, kinematic measuring is possible for tracking and robotic control. This is supported with some application examples with sample rates of 30 Hz, at the developer's website [NiM].

Some problems and limitations are reported in [MüS09], such as multipath caused by reflection and the fact that the specified measurement range of 50 m could only be achieved in a dark environment.

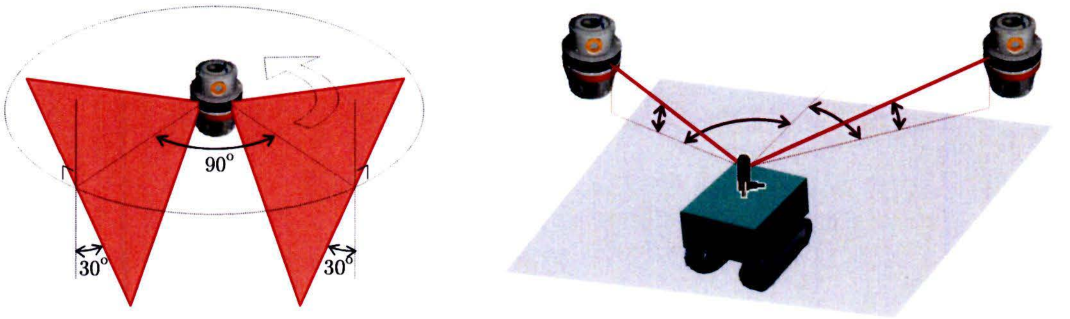


Figure 5.14: Configuration of the two rotating laser planes of a iGPS transmitter. A robot needs at least two transmitters for localisation.

For the application of tiling, a configuration is chosen where each robot is equipped with three receivers and a computer system for signal processing. Four transmitters are installed in the room on tripods or wall mounted and their locations are programmed in the robots' controllers. All 6 DOF of both robots can be determined with (sub)-millimetre accuracy.

5.3 Discussion and Evaluation of Concepts

iGPS offers a complete and easy solution for robot localisation. On the construction site, tilers have to install the transmitters and do not have to reposition or calibrate the system for a new row to be tiled. iGPS is expected to achieve tile-to-tile accuracy over the full floor.

Despite this great prospective, the system is still under development. It will be one of the first times iGPS will be put into action for high-end kinematic robot localisation. Because of all the equipment that is needed and software that has to be developed, this system is expected to be expensive.

An inclinometre is a very applicable solution for φ,ψ-feedback. It is a cheap sensor in relation to its attainable accuracy. It provides absolute tilt information without the need for initialisation or calibration. It is highly insensitive to environmental conditions and disturbances as long as shocks or excessive vibrations are limited. This is guaranteed when mounting the inclinometre on the suspended robot body. An inclinometre is easily integrable with PLC or other machine controller systems.

Building on to prior laid tiles, also referred to as 'relative tiling', is a very different approach to that of 'absolute tiling'. Once a begin is tiled manually, the robot proceeds. All equipment is on-board the robot and nothing has to be installed in the room. This means there is no risk of workers blocking laser beams or pulling down reference points.

A mechanical system like the alignment frame, is considered to be less expensive than a computer vision system. However, it contains fragile components and is susceptible to wear, due to touching the tiles. Furthermore, due to its dimensions and inevitable inertia, an alignment frame is less suited for rapid tiling (that is: 2 seconds per tile).

Positioning tiles using computer vision, requires a system of cameras and image processing techniques. A high degree of development is needed for interpreting the images and adequately controlling the system to achieve accuracy. It is however doubtful whether the specified accuracies could be satisfied over the entire floor area, using only computer vision. Accuracy is limited by the camera capabilities and, prescribing a certain speed of tiling, the number of iterative sense-plan-act cycles is limited by the processing unit capabilities. Tile-to-tile placement have to be very accurate to keep the accumulative error within tolerances. An additional measurement system can be utilised to look after the absolute error.

To conclude, camera-based computer vision is very good for localisation problems with changing conditions (such as RoboCUP, autonomous soccer), whereas it is less applicable to perform fast and accurate positioning tasks.

Using a combination of laser systems, it is possible to obtain feedback position information for all degrees of freedom. The use of standard laser equipment is possible, which generally makes it less expensive. Standard equipment is dust and (splash) water protected but still the laser beams for measurement may be disrupted in such environments.

The inclinometre sensor, laser distance sensor and iGPS that have been reviewed, all have a measurement update rate around 25 Hz. If these systems are used for closed-loop control of the tiling robot's bodywork, maximum control bandwidth that can be achieved lies around 10 Hz. Despite this is low, it can be sufficient for a compliantly suspended heavy mass.

Provided that accurate laser equipment is selected with a sufficient update rate, it is possible to satisfy tile-to-tile accuracies over the range of an entire floor. It means that a dual measurement system (absolute and tile-to-tile) is not necessarily needed.

Despite the latter statement, it may be advantageous to have redundancy in the measurement system. In case of a temporary loss of signal, the robot is then able to continue tiling. Apart from difficulties in controlling a redundant system, accuracy can be enhanced by selecting the most trustworthy feedback information or by averaging the data.

A combination of a 3-axis accelerometre and a 3-axis gyrometre provides each robot with high-rate feedback information in case of loss of laser signal. Since integration of data introduces errors over time, the sensors suffer from drift. Beside serving as a backup, inertial sensors are useful for increasing control bandwidth.

5.4 Conceptual Design of Laser Guidance System

A measurement solution is selected, consisting of various laser systems and an inclinometre. The system is not chosen to be redundant for the sake of simplicity. It might be considered if the achieved positioning accuracy is found to be not satisfactory. This might even be concluded from tests with a prototype robot.

Figure 5.15 shows the implementation of measurement devices in the robots, situated on a floor to be tiled. The mortar robot (purplish gray) and the tiling robot (bluish gray) are equipped with identical measurement devices. Inclinometres (orange) are installed on each suspended bodywork and provide φ,ψ-feedback.

Instead of a spot laser as suggested in Section 5.2.2, a line laser (dark blue) is set up as a guide for the desired line of tiling. It projects a vertical plane in stead of a line, as can be seen in Figure 5.16. Each robot has two 1D position sensitive detectors (PSD's) mounted on each corner, by which y and θ position can be determined. These sensors cannot be mounted on the same height as they block the laser beam for the sensors behind them. It means that y and θ feedback signals are slightly coupled to φ. The placement of PSD's is such that the laser beam is always detectable by both robots; even if the tiling robot is at the beginning of a row and blocks the broadest view. As the positioning of the mortar robot is allowed to be less accurate, its PSD's are placed the farthest apart.

It is suggested to mount the above described line laser on a long linear rail. For the length of the rail (about 2 to 3 m), it allows a quick reinitialisation when starting to tile a new row.

Next to the laser, reflectors are mounted on this linear guidance system. The reflectors are part of the laser distance measurement systems, which are placed on the robots (light blue). To avoid interference with the laser plane projection, the sensors are mounted more inside the robot. The sensor of the tiling robot is placed in line with the tile's centre. The sensor of the mortar robot is placed next to the caterpillar tracks and its beam passes through the tiling robot.

A multi-line laser is installed in the corner of the room and emits a horizontal reference plane. It is detected by 1D PSD's on the robot (green) and provides feedback on the robots z-position. This laser moreover projects a cross on the floor which is useful to align the linear guide and accompanying line laser, especially when initialising the first row.

The presented measurement system design is a start. Various things needs further investigation, such as the positioning of PSD's on the robot, the acute angle of incidence from the z-plane laser when tiling the first rows and a method for obstacle and end-of-row detection. Furthermore, there are opportunities in the development of mechanisms to easily fine-align the laser beams and systems to easily set up and initialise the linear rail guide.

The above presented system has the feature that only robust sensors are mounted on the robots. The more delicate instruments (the multi-line laser and linear guidance system) are separated from the robots. They should be handled adequately and are to be transported in solid carrying cases.

Furthermore, the presented setup features the possibility to tile the non-automatically tiled areas manually while the robot is in operation: Workers do not have to block essential laser beams or otherwise disturb the robots in operation.

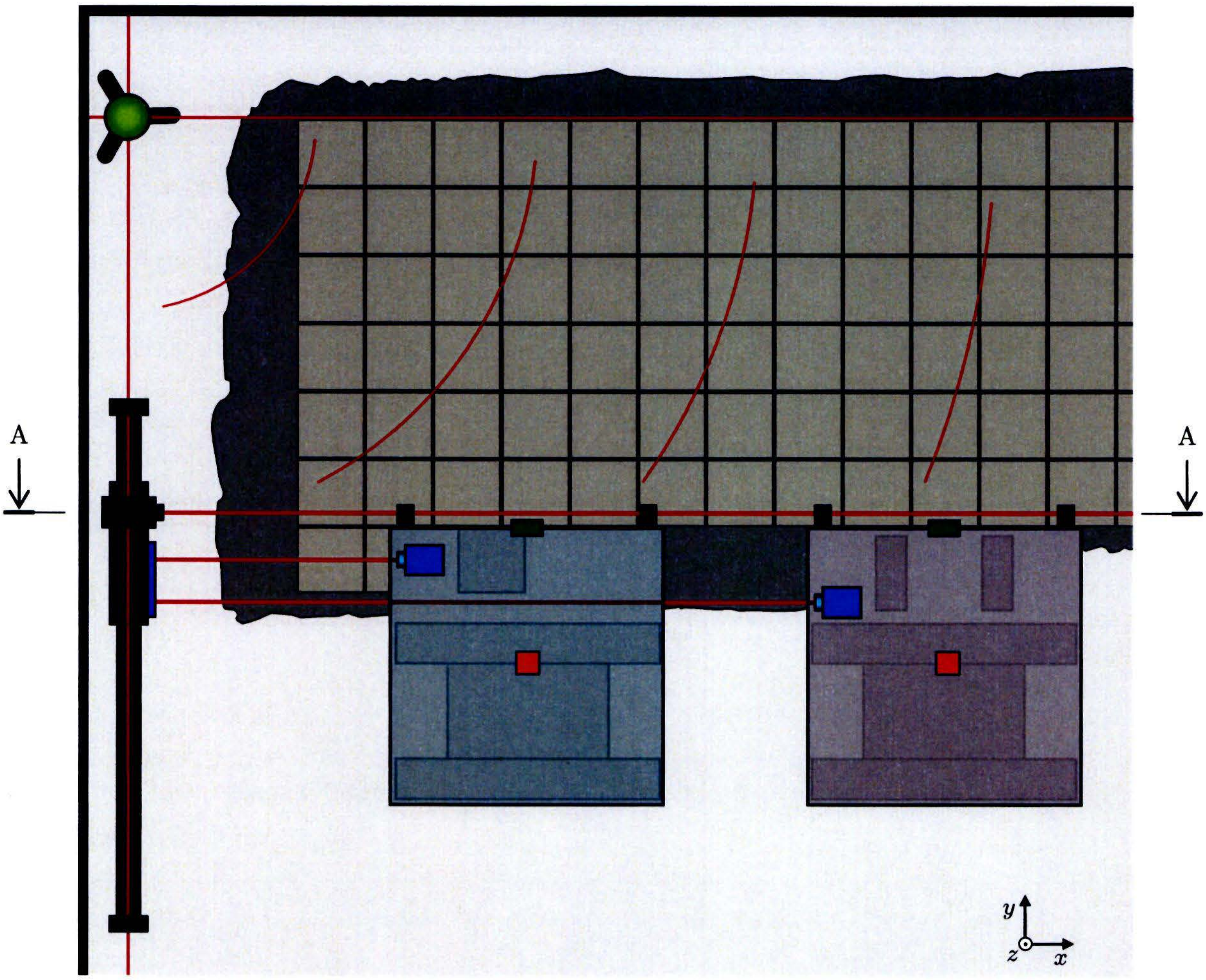


Figure 5.15: Illustration of the proposed measurement system for 6-DOF feedback. It features laser plane projection for z (green), vertical plane projection along the line of tiling for y and θ (blue), laser distance measurement for x (light blue) and inclinometres for φ and ψ (orange).

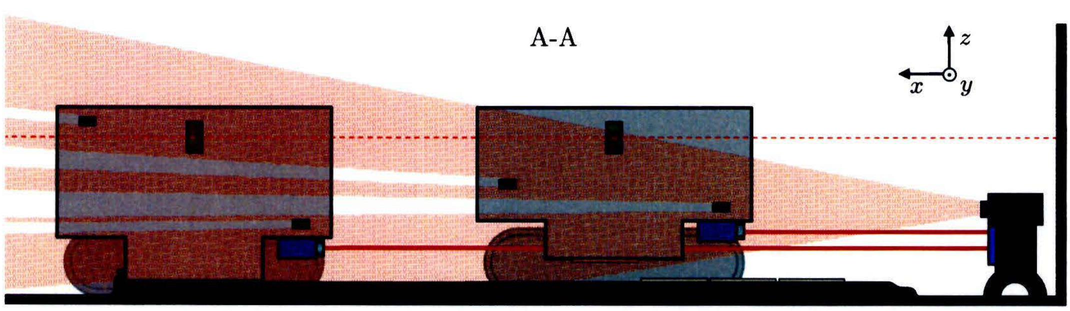


Figure 5.16: Cross sectional view A - A of Figure 5.15 showing the projected laser plane along the desired line of tiling.

Chapter 6

Active Suspension

Section 3.5.5 proposed to control the tiling robot's body to stay parallel and in-plane to the line of tiling. From this 'floating' body, tiles are aligned and fixed to the mortar bed.

The robot body and all tiles on it, are controlled in 5 DOF with respect to the undercarriage. The last DOF, coinciding with the direction of tiling, is not necessarily controlled with respect to the undercarriage, as the tile's x-position is aligned by the placement device during tile placement.

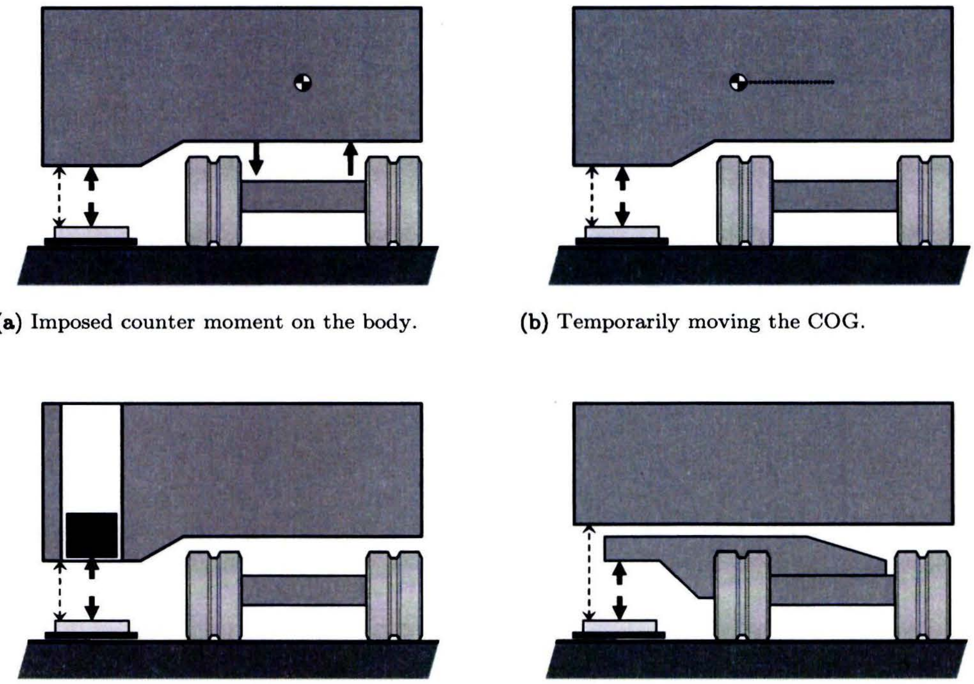
To isolate the robot body from the rough construction floor and from vibrations caused by running the undercarriage tracks, the robot body is suspended on the undercarriage. Good isolation is achieved with a large robot body mass and a compliant suspension.

The benefit of having a large mass is that unwanted process forces and other disturbance forces acting on the body have small effect on the bodywork's position. However, process forces concerning the placement and fixation of tiles, are of that magnitude that they can not be considered negligible. Moreover, this force acts on the robot very eccentrically.

To deal with the tile placement force, different solutions are possible. Four concepts are depicted in Figure 6.1. All four feature a suspended bodywork that performs positioning of tiles simultaneously. Figure 6.1a shows a solution where the placement reaction force, acting on the body, is counteracted by an imposed moment. In Figure 6.1b, the counteraction is performed by temporarily moving the centre of gravity (COG) towards the placement device.

Figure 6.1c and 6.1d features a separation of the force handling from the tile's positioning. In Figure 6.1c, the placement reaction force is induced on a counter mass, freely suspended on the robot's body. In Figure 6.1d, the placement reaction force is induced on the undercarriage.

A travel of the COG can only be established by moving mass on the body. Moving a mass yields a counter acceleration force in horizontal direction which disturbs the body's controlled position. A separated positioning and force application presumably requires the applied force to be regulated in a closed loop control scheme. It probably results in a more complex design.



(a) Imposed counter moment on the body. (b) Temporarily moving the COG.

(c) Reaction force induced on a free mass. (d) Reaction force induced on the undercarriage.

Figure 6.1: Various concepts for counteracting the tile placement reaction force.

The first configuration is chosen for its simplicity. No additional moving parts are required. The effect of a tile placement reaction force, acting on the suspended body, should be sufficiently diminished in an energy effective way.

This chapter discusses some aspects on the stability of the robot, in particular when placing a tile. A conceptual design of the bodywork's suspension is presented and its dynamical behaviour is examined.

6.1 Static Stability Aspects

The non-symmetrical structure of the robot makes it necessary to consider weight distribution and stability aspects.

Good stability is achieved when the COG is on the central axis of the undercarriage, as low as possible. On the other hand, the counteracting effort is less when the COG is closer to the vertical axis of tile placement. Deadweight can then be used for counteraction.

6.1.1 Centre of Gravity of the Body

An estimation of mass is made of various subsystems on the robot, as well as the locations of their COG's. This is depicted in Figure 6.2 (left). To lower the COG, a heavy power unit is supposed in between the caterpillar tracks and mounted on the suspended body.

The position of the COG of the entire tiling robot body is calculated as the weighted mean of the COG's of the subsystems, shown in Figure 6.2 (right).

The decline of mass caused by applying tiles and bond coat paste to the floor is incorporated and is depicted with a gray COG symbol for empty cartridges and container.

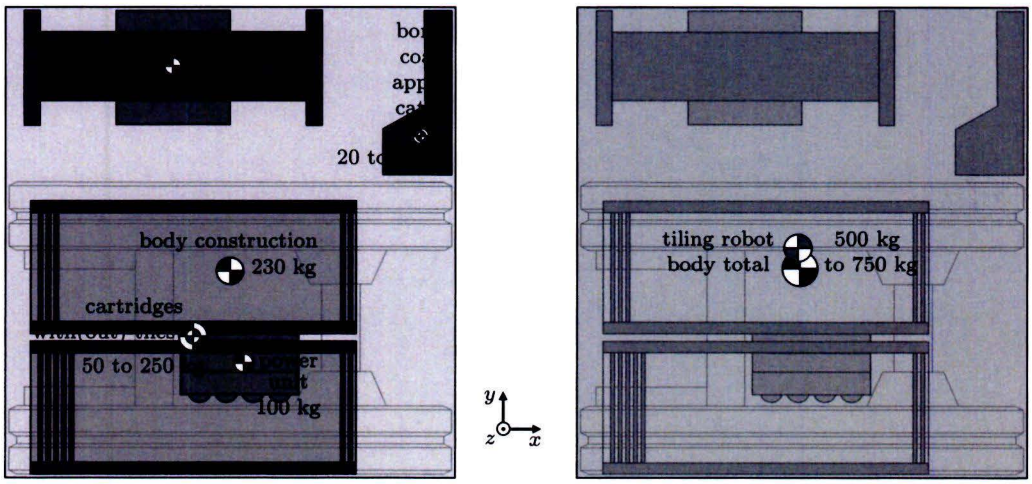


Figure 6.2: The position of the COG of the tiling robot body in the xy-plane is determined from the COG's of various subsystems.

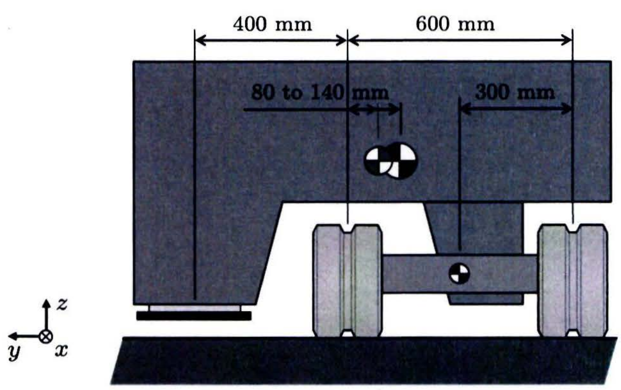
It is found that the COG lies more or less on the central axis of the suspended body. In the x,z-plane, it gives a good stability around ψ, provided that the COG is low. In the y,z-plane however, the position of the COG is far from the cental axis of the undercarriage, which results in an unequal distribution of load to the caterpillar tracks.

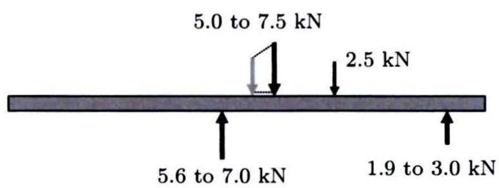
The location of the COG can be modified by rearranging components. However, attempts to move the COG close to the central axis of the undercarriage needs major changes and seems to be only realisable by adding deadweight on the edge side of the body, or enlarging the body dimensions and creating an overhang also on the other side, or by arranging subsystems on top of each other. As these solutions each have their disadvantages, an unequal wear of the tracks due to an unequal load is preferred above the others.

6.1.2 Weight Distribution on the Tracks

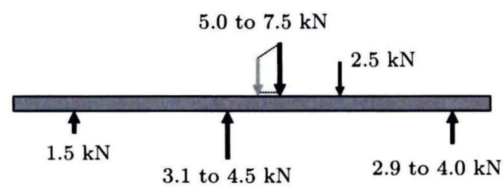
In Figure 6.3a, the weight distribution over the two tracks is evaluated with the COG horizontal location as determined in Figure 6.2. The placement of a tile induced a reaction force on the robot with an estimated maximum of 1.5 kN. This situation is evaluated in Figure 6.3b. Note that this simplified model only considers vertical forces in the y,z-plane.

During the full sequence of tiling, the force on a track is at most 7 kN. This lies around the weight limit specified by the manufacturer (Appendix B.4). Exceeding the weight limit presumably result in accelerated wear, but the 7 kN will only be faced shortly.





(a) Dead weight pressure.



(b) Dead weight pressure with assembly force.

Figure 6.3: Vertical forces acting on a simplified robot model, used for evaluating weight distribution. Track pressure decreases by unloading tiles from the robot.

6.1.3 Tip-Over Stability of the Robot

As the COG lays close to a track in the y,z-plane, tip-over stability of the robot is analysed in Figure 6.4. Using the same subcomponents as analysed in Figure 6.2, the height of the COG of the entire robot is estimated to be varying between 350 and 400 mm.

Figure 6.4 shows an extraordinary situation of a tilted robot (further tilting is limited by the tile placement device). For tipping over, it would still need an additional force of more than 1.2 kN, which is hardly achievable through human effort.

6.2 Design of the Body Suspension

A suspension system is suggested, using air springs for levelling the body and compensating deadweight, and electro-mechanical actuators for final positioning and actively reducing vibrations. Air springs are advantageous as they offer high compliancy, are light-weighted and occupy a small space.

To compensate the body's deadweight, one big air spring straight under the COG is sufficient. The position of the COG however may vary ± 30 mm or even more, depending on the method and sequence of unloading tiles from the cartridges. To compensate this with the electro-mechanical actuators, requires them to permanently generate a balancing force.

A system of three air springs with complementing levelling system is suggested. Height

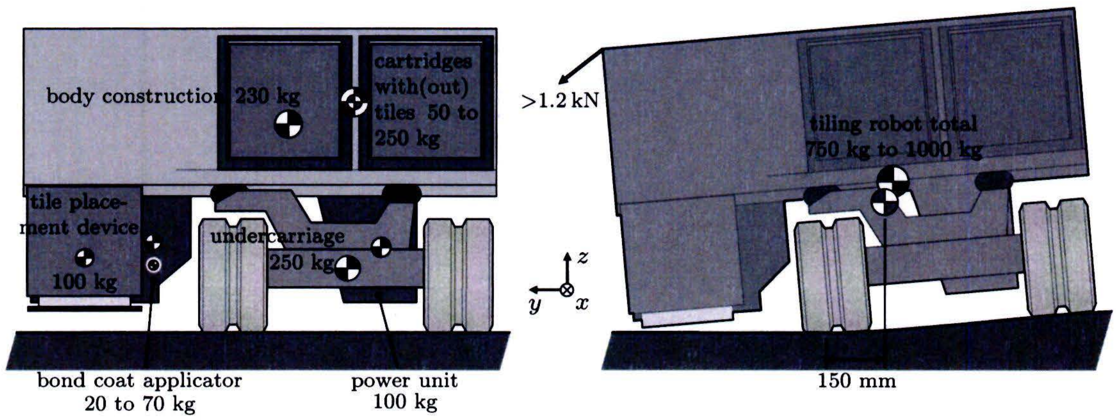


Figure 6.4: The COG in the y,z-plane is determined and tip-over stability of the robot is analysed.

and inclination of the body can be adjusted by inserting or releasing air from the springs with electro-mechanical valves. As the response of air regulation is presumably too slow for accurate positioning, the electro-mechanical actuators are placed in parallel to increase control bandwidth.

The system is visualised in Figure 6.5. The three air springs (purple) can deal with a travelling COG by regulating their pressure separately. A blue dotted line shows the estimated contour in which the COG may travel. The electro-mechanical actuators are initially imagined as joined with the air springs, but can be placed anywhere else underneath the robot's body.

The locations of air springs should be chosen such that the COG lies always inside the contour that surrounds the air springs (green). Placing the springs far apart increases mechanical levelling resolution compensating tilt, but also decreases the angular compliancy of the suspension. Selecting the ratio between eigenfrequencies in z, φ and ψ-direction is possible by placing the air springs far apart or close to each other and by changing the angle of the triangle.

A configuration of three air springs gives the body a three-point support. A configuration of four air springs is also possible where two springs are connected.

6.2.1 Counteraction of the Tile Placement Force

While placing a tile, or more specifically, bringing the tile to its desired position, the bond coat cement paste and mortar bed is compressed. It induces large reaction force on the body, which can be up to 1.5 kN. Furthermore, the location of the net placement force is likely not at the exact centre of a tile but may vary. The latter is indicated with the red dotted contour in Figure 6.5.

Figure 6.6 examines the effect of the placement force. It shows the reaction forces on the three supports for the static case of a fully loaded robot (left), and in case the maximum tile placement force is statically acting on the body on top of that (right).

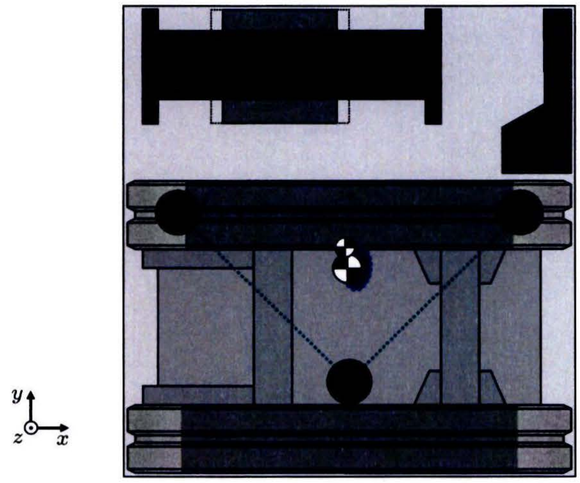


Figure 6.5: Proposition on the location of the air springs to suspend the tiling robot's body. It also indicates the COG and its variation, and the area where the net placement force can act.

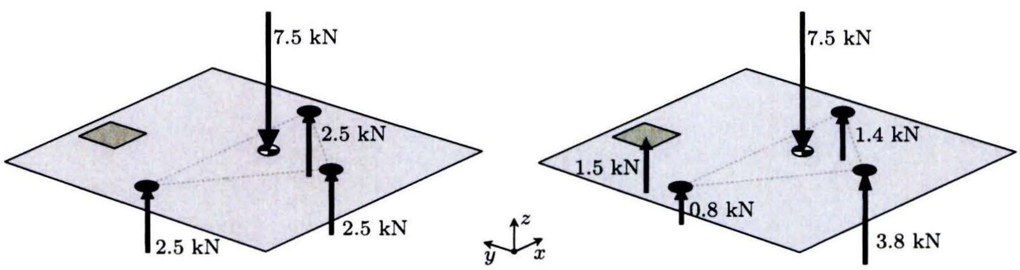


Figure 6.6: Load support, analysed in a horizontal section of the robot body.

The change in support forces can be up to 1.7 kN with the given configuration. Under position-feedback operation, the electro-mechanical actuators will counteract the change in support forces and adapt the levelling system of the air springs with a much larger time constant.

However, as the instant of placement is known, feedforward can be utilised in the control loop. A force equal to the expected reaction force is applied to the levelling system by the electro-mechanical actuators, or by other means of creating a counteracting force.

6.2.2 Selection of Air Springs

Figure 6.6 shows that the static load on an air spring is 2.5 kN. Furthermore, for levelling both height and inclination, the air springs are determined to have a maximum stroke of $\pm$ 30 mm.

Air springs are widely used in automotive and also in industrial applications for vibration control. The single convolute air spring FS 70-7 from ContiTech for example meets the requirements. For bearing a load of 2.5 kN, it needs over the stroke of 64 mm, 2 to 4 bar pressure. At the recommended height, the spring rate is specified to be $1.0 \cdot 10^5$ N/m [CCT].

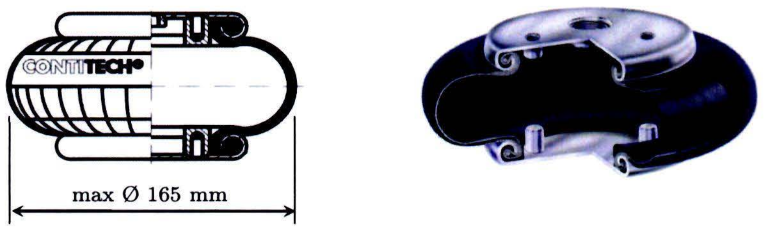


Figure 6.7: Single convolute air spring FS 70-7 from ContiTech [CCT].

6.3 Dynamic Behaviour

To evaluate the body suspension design, and to conclude on the isolation of vibration, a dynamical model is derived.

Only the dynamics in z and φ are considered in the cross-sectional y,z-plane. Because the reaction force from tile placement, acts on the body eccentrically, it will have a big influence on the body's stability. Furthermore, one of the lowest eigenfrequency is expected to occur in this y,z-plane, namely of the rotation of the body in φ.

6.3.1 Dynamical Model

Figure 6.8 gives a representation of the robot's dynamical model, consisting of the undercarriage and bodywork. Their positions and angular orientations are considered at their COG's.

The height and tilt of the tile placement device are of interest and denoted with z_{tpd} and φ_{tpd}. The bodywork suspension is modelled with spring stiffnesses c_{sl} and c_{sr} and actuator forces U_l and U_r. Here, c_{sl} and U_l are containing the two supports behind each other.

The rubber tracks are modelled with spring stiffness c_t. Components that disturb the robot are the rough floor profiles underneath both tracks, prescribed by z_{gl} and z_{gr}, and the reaction force from tile placement, modelled as a variable force source F_{dist}. Relevant dimensions are declared with variables.

For simplicity, φ angles are assumed to be small, which is true for normal robot operation. This justifies the use of a linear approximation, where φ is specified in radians.

Using force-balance analysis of the model in Figure 6.8, linear equations of motion are derived and represented in state-space format

$$\left\{ \begin{array}{rcl} \dot{\underline{z}} &=& A\underline{z} + B\underline{u} \\ \underline{w} &=& C\underline{z} + D\underline{u} \, . \end{array} \right. \tag{6.1}$$

The state vector $\underline{z}$, the input vector $\underline{u}$ (containing inputs and disturbances) and output description $\underline{w}$ are defined as

$$\underline{z} = \begin{bmatrix} z_1 & \dot{z}_1 & \varphi_1 & \dot{\varphi}_1 & z_2 & \dot{z}_2 & \varphi_2 & \dot{\varphi}_2 \end{bmatrix}^{\mathrm{T}},$$

$$\underline{u} = \begin{bmatrix} F_{\mathrm{dist}} & z_{gl} & z_{gr} & U_l & U_r \end{bmatrix}^{\mathrm{T}},$$

$$\underline{w} = \begin{bmatrix} z_{\mathrm{tpd}} & \varphi_{\mathrm{tpd}} \end{bmatrix}^{\mathrm{T}}.$$

The matrices A, B, C and D of state-space equation **(6.1)** are given below.

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-2c_t - c_{sl} - c_{sr}}{m_1} & 0 & \frac{s_l c_{sl} - s_r c_{sr}}{m_1} & 0 & \frac{c_{sl} + c_{sr}}{m_1} & 0 & \frac{-(s_l - q)c_{sl} + (s_r + q)c_{sr}}{m_1} & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ \frac{s_l c_{sl} - s_r c_{sr}}{J_1} & 0 & \frac{-2p^2 c_t - s_l^2 c_{sl} - s_r^2 c_{sr}}{J_1} & 0 & \frac{-s_l c_{sl} + s_r c_{sr}}{J_1} & 0 & \frac{s_l(s_l - q)c_{sl} + s_r(s_r + q)c_{sr}}{J_1} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ \frac{c_{sl} + c_{sr}}{m_2} & 0 & \frac{-s_l c_{sl} + s_r c_{sr}}{m_2} & 0 & \frac{-c_{sl} - c_{sr}}{m_2} & 0 & \frac{(s_l - q)c_{sl} - (s_r + q)c_{sr}}{m_2} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ \frac{-(s_l - q)c_{sl} + (s_r + q)c_{sr}}{J_2} & 0 & \frac{s_l(s_l - q)c_{sl} + s_r(s_r + q)c_{sr}}{J_2} & 0 & \frac{(s_l - q)c_{sl} - (s_r + q)c_{sr}}{J_2} & 0 & \frac{-(s_l - q)^2 c_{sl} - (s_r + q)^2 c_{sr}}{J_2} & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{c_t}{m_1} & \frac{c_t}{m_1} & \frac{-1}{m_1} & \frac{-1}{m_1} \\ 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{-pc_t}{J_1} & \frac{pc_t}{J_1} & \frac{s_l}{J_1} & \frac{-s_r}{J_1} \\ 0 & 0 & 0 & 0 & 0 \\ \frac{1}{m_2} & 0 & 0 & \frac{1}{m_2} & \frac{1}{m_2} \\ 0 & 0 & 0 & 0 & 0 \\ \frac{-r+q}{J_2} & 0 & 0 & \frac{-s_l+q}{J_2} & \frac{s_r+q}{J_2} \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 & -r+q & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

$$D = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

For evaluation and simulation of the model, parameters are substituted with values, given in Table 6.1. The geometric parameters result from the outlined design in Figure 6.3 and 6.5, relative to a 300 mm tile. At average installation height, the air spring stiffness is given by the manufacturer. For the rubber track stiffness, an estimation is made based on Hooke's law using a rubber Young's modulus of 6 MPa, similar to truck tyre rubber, a rubber thickness

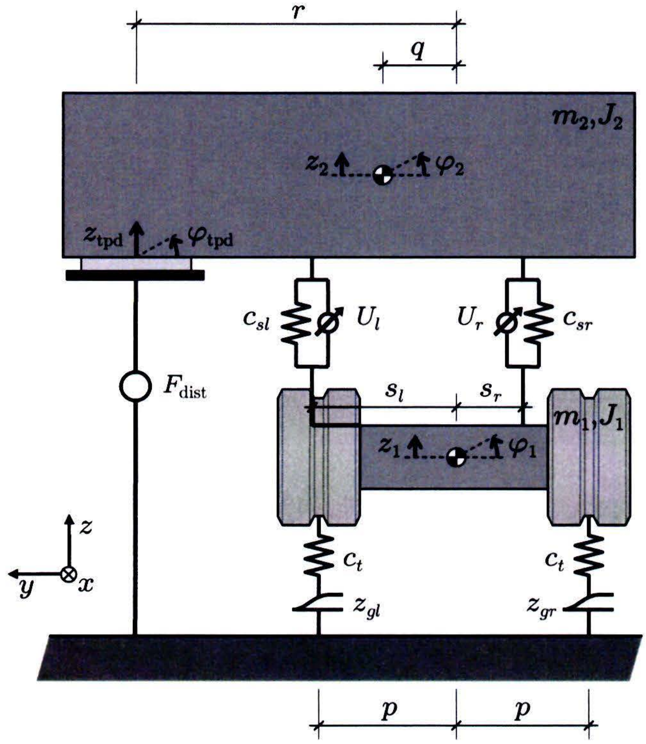


Figure 6.8: Dynamical model of the robot in z and φ dimension.

Parameter	Value	Unit
p	0.300	m
q	0.160	m
r	0.700	m
s_l	0.140	m
s_r	0.310	m
c_t	$2 \cdot 10^6$	N/m
c_{sl}	$2.0 \cdot 10^5$	N/m
c_{sr}	$1.0 \cdot 10^5$	N/m
m_1	250	kg
J_1	40	kg m^2
m_2	750	kg
J_2	115	kg m^2

Table 6.1: Parameter values are used to evaluate the dynamical model.

of 30 mm and a 75% effective supported area of ten carved segments of each 0.07 × 0.02 m^2 (Appendix B.4). Masses and inertias are derived from the outlined design in Figure 6.4.

While unloading tiles and bond coat paste, the parameters q, c_{sl}, c_{sr}, m_2 and J_2 vary, and while adjusting height and level, the air spring stiffnesses c_{sl} and c_{sr} vary. The dynamic behaviour is further analysed for the situation of a fully loaded robot, adjusted at average height.

6.3.2 Frequency Response Analysis

Figure 6.9 gives the frequency response function from the disturbance force F_{dist} to the output z_{tpd} in a Bode magnitude plot.

The transfer function shows four resonance frequencies. The four frequencies are denoted in Figure 6.10 together with their corresponding mode shapes.

The effectiveness of the suspension to isolate z_{tpd} from vibrations caused by floor unevenness and enveloping the tracks, is demonstrated in Figure 6.11. It shows the transmissibility from vibrations on z_{gl} and z_{gr}, to the output z_{tpd}.

Vibrations with frequencies above 4 Hz are reduced in magnitude. Vibrations with low frequencies are even increased, especially at the resonances frequencies. A controller with a sufficient bandwidth is able to diminish this dynamics.

Note that no damping is included in the model, which explain the high peaks. Furthermore, only the magnitude response is shown as the phase response is of less interest for vibration reduction.

The rubber track profile has thicker segments with a pitch of 72 mm. When riding 150 mm/s, resulting vibrations at 2.1 Hz likely have a considerable effect on the robot.

6.3.3 Time Response Analysis

The tracks are simulated to drive onto a 30 mm obstacle with a speed of 150 mm/s. The suspension, located at half the length of the tracks, faces half the obstacle height. Local rubber deformation is not included in the model: A simple trapezoidal step to 15 mm height in 0.6 s is given as an input.

Figure 6.12 shows the behaviour of the body at the placement device (z_{tpd}), where input z_{gl} and input z_{gr} are excited, successively. The simulation shows free responses of the robot body to the given disturbance inputs as no control is applied. After excitation, the output z_{tpd} possesses an oscillation with frequency 1.5 Hz. Figure 6.12 (right) shows an opposite behaviour to the reference signal as z_{gr} lies on the other side of the COG.

A successfully implemented controller should reduce a deviation of the body towards zero, after excitation of the undercarriage.

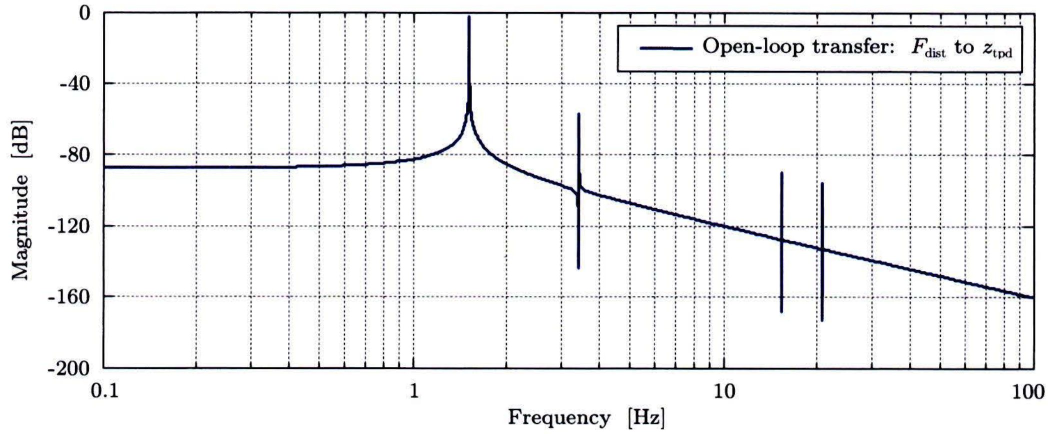


Figure 6.9: Bode magnitude plot from a disturbance force F_{dist} to the output z_{tpd}.

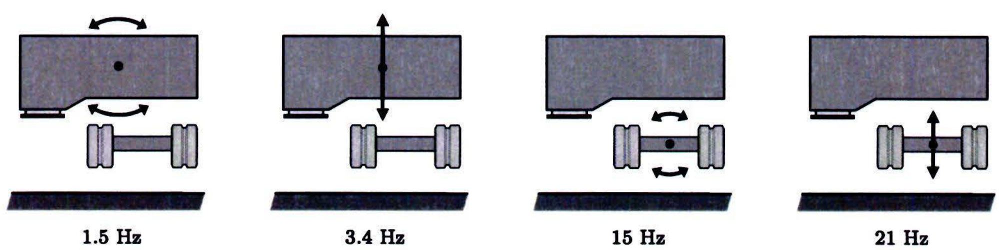


Figure 6.10: Resonance frequencies of the two-mass system with corresponding mode shapes.

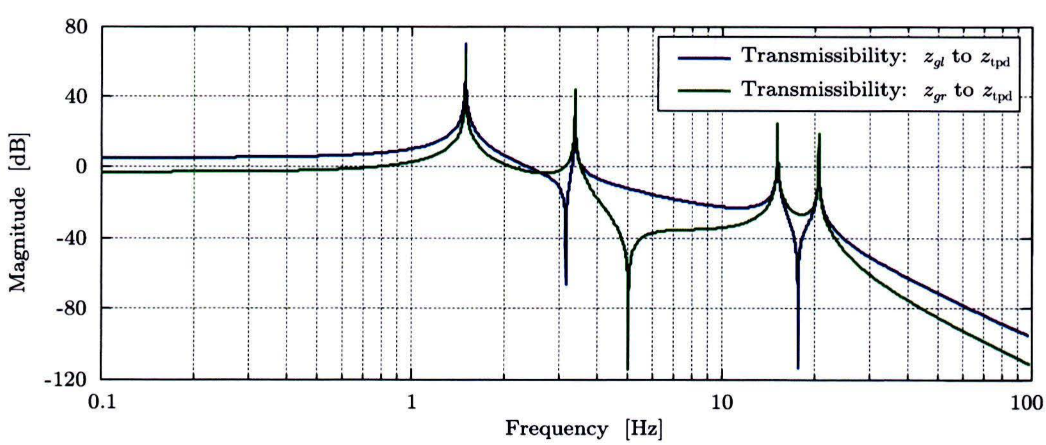


Figure 6.11: Bode magnitude plot of the transmissibility from the disturbances z_{gl} and z_{gr} to the output z_{tpd}.

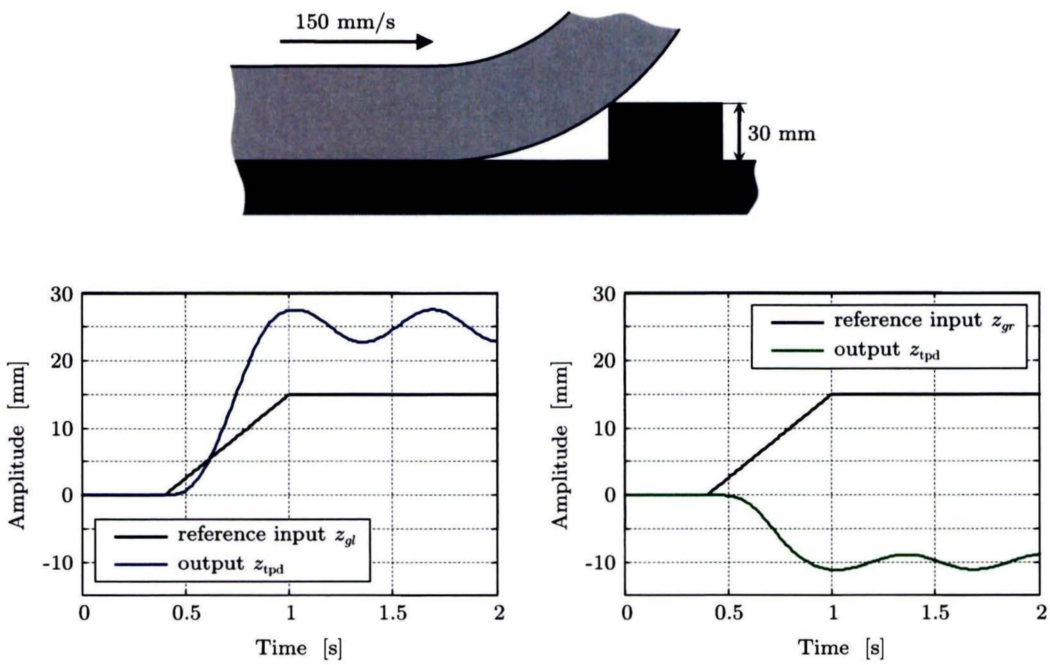


Figure 6.12: Time response at z_{tpd} to a reference input, simulating riding over a 30 mm obstacle with a speed of 150 mm/s.

6.3.4 Controller Design

Tracking accuracy is achieved with a good controller design, though this goes beyond the scope of this thesis project. Simulating the presented dynamical model with an implemented controller gives an outlook on the actual performance of the active levelling system and, together with expected mechanical uncertainties, whether the specified inaccuracies can be achieved.

As the 2D-model has two inputs to control two outputs, a MIMO-controller comes into use. The controller should be robust and adaptive to variation in masses and stiffnesses.

The bandwidth of the controller is limited by the update rate of the measurement systems used. For the suggested configuration of measurement sensors, and taking the commercial sensors presented as an example, this control bandwidth is approximately 10 Hz for φ, limited by the 25 Hz update rate of the inclinometre. In this degree of freedom, passive isolation is effective above the φ-resonance at 1.5 Hz. Active isolation is effective up to the control bandwidth of 10 Hz.

Likewise exciting z_{gr} shows opposite behaviour to the output, the transfer from a control input U_r to the output has the same characteristics. Furthermore, due to antiresonances, the control of the body has some control invariant points. Having damping diminishes this effect.

6.4 Conclusion

Analysis of the COG of the body, shows that it may vary up to 60 mm in y-direction. The combined COG lies off the central axis of the undercarriage. Because of this, the rubber tracks are loaded unequally and will face unequal wear. This is encountered as the downside of the design with an overhang.

A levelling system consisting of three air springs and three electro-mechanical actuators is suggested for passive and active isolation of vibrations, and for accurate position control of the body.

The transmissibility of vibration is evaluated with a dynamical model in z and φ. At the tile placement device, it gives a passive reduction of vibrations above approximately 4 Hz. For an active reduction of low frequent vibrations, an adequate controller is needed.

The presented suspension design considers z,φ,ψ with an analysed dynamical behaviour in z,φ. A less critical solution is to be found for x,y,θ suspension and position control.

Chapter 7

Tiling Robot Design

This chapter elaborates on the design of the tiling robot in more detail. First an overview is given of the tiling robot design, showing main components. The next sections will elaborate on the design of the tile placement device.

7.1 Overview of Main Components

Figure 7.1 shows a sketch of the tiling robot with the layout as discussed so far. The robot body is suspended on an undercarriage with rubber tracks. The bond coat applicator is shown in green; it extrudes a notched film of cement paste on the mortar bed. Also two tile cartridges are shown. Tiles are to be lead from the cartridge to the mortar bed, indicated with the long purple line. The tile placement device shown in blue takes the tile and installs it on the floor.

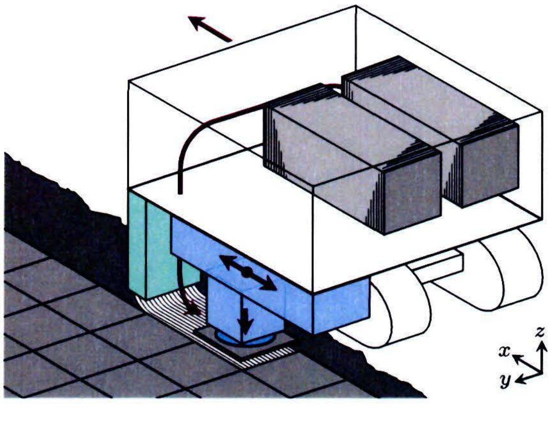


Figure 7.1: Sketch of the tiling robot, showing a tile cartridge, bond coat applicator and tile placement device.

7.2 Internal Tile Alignment

The robot's bodywork, including the tile placement device, is actively controlled to place tiles from this aligned position. Initially, the tiles that are loaded on the robot are not aligned with respect to the robot body. Each tile's geometrical centre and angular orientation should be searched in the x,y,θ-surface, prior to installation of the tile on the floor. The two aligning steps are visualised in Figure 7.2.

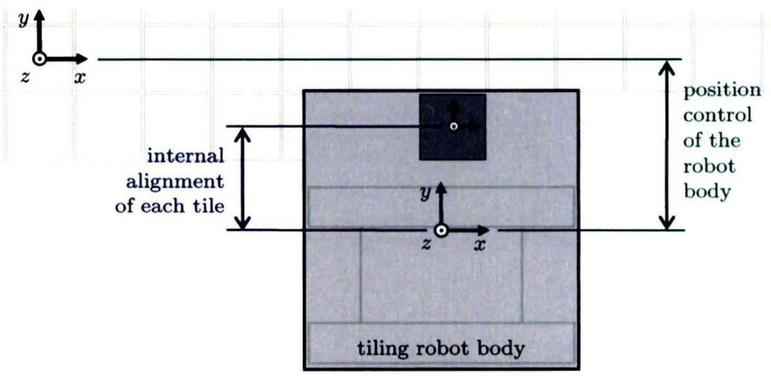


Figure 7.2: The robot body is aligned to a floor reference. A tile is aligned to the robot body.

It is suggested to align the tile during transport of tiles from the cartridge to the place of presentation to the placement device. The tile placement device then can grip a tile, having an aligned centre. To transport the tiles towards the placement device, a series of conveyor belts or robotic manipulators is used. Searching the tile's centre can be done by sensing the tile and applying a correction, or by temporarily clamping the tile with a symmetrically closing mechanism.

The tile's internal transport is not further elaborated in this report. Its main objective is to present tiles to the placement device where each defined centre lies always on the same spot. The placement device then grips the tile and, with perfect straight movements, it places the tile on the floor.

It is important that mechanical components concerning the handling of tiles during the last steps are accurate within submillimetre range. As these systems are outside the closed controlled loop, abberations in placement will show up in the tilework.

Systematic errors are of less concern than random errors. Systematic errors in x and y result only in a overall shift of the tiles with respect to the desired tiling grid. This can be tolerated if it is not referred to anymore. The random errors in tile placement strokes are part of the total placement inaccuracies, together with uncertainties in the measurement system, control tracking errors, bond coat resiliency after tile placement, etcetera.

7.3 Tile Gripper Design

Once the tile is presented near the placement device, it is ready to be picked up by the gripper of the placement head. The tile's geometrical centre and angular orientation in x,y,θ already has been determined and is taken over by the gripper with a reproducible stroke.

The average plane of the tile's top surface in z,φ,ψ is to be determined by the gripper during pick up of a tile.

7.3.1 Six-Point Support with Whiffletrees

In general, a tile's top surface is unlikely to be flat but may be convex, concave, slanted or curved (see size and shape variations in Table 3.3).

Another important aspect to consider is the fragility of the tile. Point contacts may break the tile, and therefore thin rubber pads are suggested for a gentle tile gripping. These pads should however not be too compliant as the actual position of the tile is not observed by the gripper. Depending on the tiles' characteristics, a rubber pad of 0.5 to 1 mm thickness would be sufficient.

For a better distribution of forces over the tile, and moreover to have a better approximation of the average plane, whiffletrees are suggested. The construction of three whiffletrees projects a hexagon on the square tile. This can be seen in Figure 7.3 together with a suction cup. Gripping the tile's surface by rubber pads occur at the six points D,E,F,G,H,I. The three whiffletrees are hinged on three points A,B,C to obtain a statically determined gripping in z,φ,ψ. As adapting angles are small, elastic hinges are most suitable.

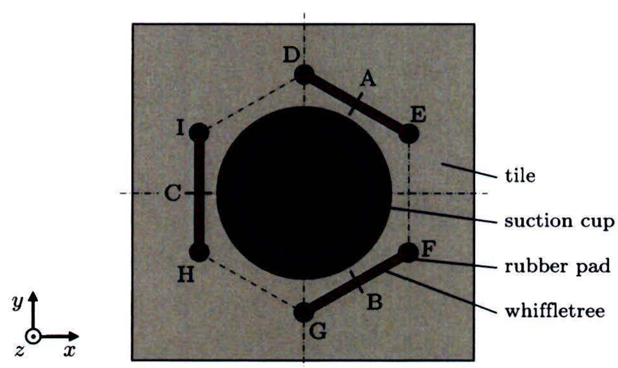


Figure 7.3: Gripper design outline, featuring three whiffletrees and a suction cup.

7.3.2 Suction Cup

As tiles typically have a coated or glazed surface, vacuum is very suitable to grip tiles. Another option is clamping, as used for machine-laid paving (see Appendix B.1). This however requires wider tile joints. Moreover, it is difficult to cope with the non-straightness of the tile edge.

A suction cup is able to adapt to the slightly non-flat top surface. Yet, porous tiles or tiles with a very rough top surface may encounter problems on secure gripping. To cope with small leakages, a suction cup with a large volume maintains a more constant underpressure. However, this also makes that it takes longer to build up vacuum in the cup. For a quick application of vacuum, a buffer tank can be used. When opening a valve, air is sucked out of the cup.

Figure 7.4 shows an applicable large volume suction cup with a specified maximum suction force of 370 N. Compared to forces from acceleration of the tile, this force is large. Yet, to stick to the rubber pads by friction even at lateral forces during placement, sufficient tension force is needed.

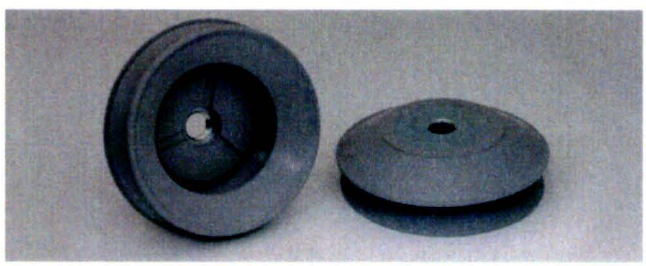


Figure 7.4: A 1.5-folds suction cup from Schmalz with an effective diameter Ø 150 mm and a designed suction force of 370 N [Sch].

7.3.3 Tile Simulation using a Finite Element Method

FEM-analysis is used to examined the fragile tile under the load of vacuum in the suction cup, the whiffletree support and the mortar counterforce during placement.

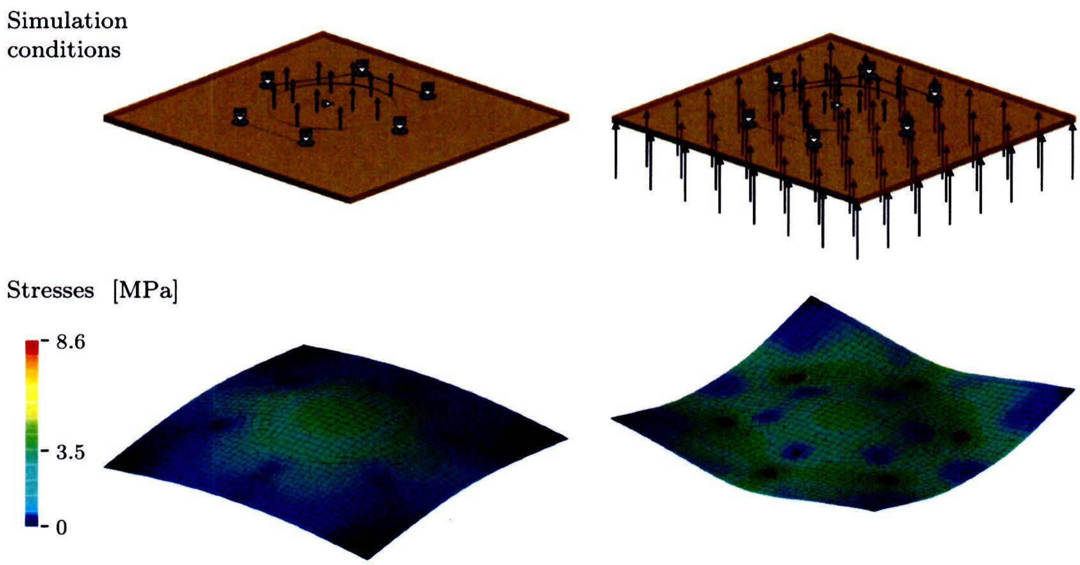
The first situation in the handling of tiles that is considered, is where the tile is gripped by the placement head at the pickup position (Figure 7.5a). The suction cup pulls the tile onto the six rubber pads of the whiffletrees.

The suction cup is modelled as a force of 350 N, pulling over a circular area of Ø 150 mm. The tile is simply supported representing the rubber pads, where the reaction forces are spread over six circular areas of Ø 12 mm.

As a tile is a thin, plate-shaped structure, a 2D-mesh is used to model the tile's mid-plane. A denser mesh is applied near the Ø 12 mm rubber pads. Actual tile dimensions and material properties that are used, are listed in Appendix A.3.

In Figure 7.5b, the second situation is analysed where the tile is being installed on the mortar bed: A maximum counterforce of 1.5 kN is facing the tile's back.

The deflected shape of the tile under load is visualised with 500× magnification and reaches a maximum of 0.05 mm. Stresses in the tile reach a maximum of 8.6 MPa.



(a) A tile is gripped by the whiffletrees and suction cup.

(b) A tile is gripped by the whiffletrees and suction cup, and facing counterpressure of the mortar.

Figure 7.5: FEM-analysis of a tile during gripping and placing.

Note that tile manufacturers specify a minimal bending strength for their tiles. The sample tile of Mosa has a prescribed bending strength of 40 MPa, as also denoted in Appendix A.3. The EN-14411 standard for ceramic tiles specifies a lower bending strength of 25 MPa.

A safety factor of about 3 is shown in the modelled situation. However, real load situations and tile behaviour likely differ from the modelled uniformity. Tests with a gripper prototype can be a next step in gripper design and optimisation.

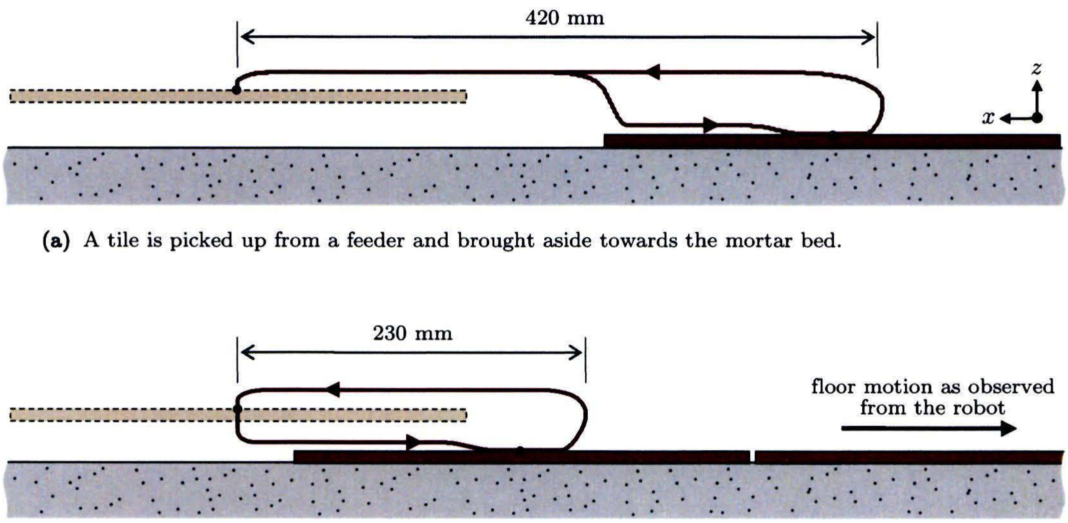
7.4 Presenting a Tile to the Placement Device

Two possible ways for picking up a tile by the gripper are compared next. After gripping the tile, it can either be taken up and move aside, or pushed down.

As seen from the moving robot, the motion path of the tile's top centre (coinciding with the origin of the coordinate system as defined in the preamble of this report (Figure 1)), is represented for two configurations in Figure 7.6.

The top configuration yields higher velocities and accelerations as more distance has to be covered in the same time interval. Together with the change in the direction of motion after pick up, it will disturb the bodywork to a larger extend.

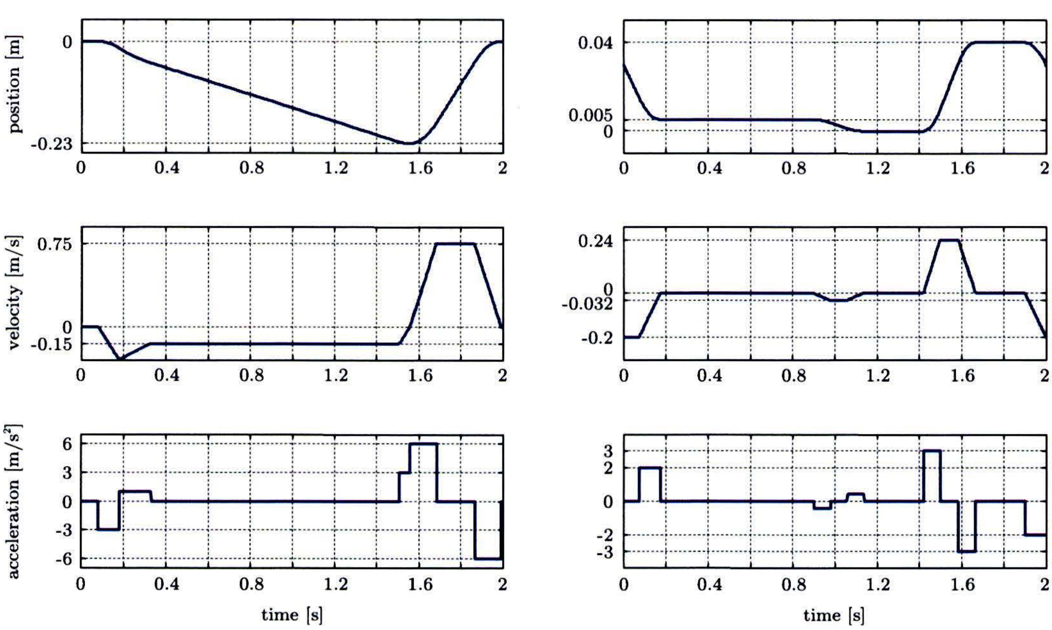
The bottom configuration is chosen for its continuous motion path. It brings forth that a reliable push-down system has to be developed. A tile may only be released if it is secured to the placement head.



(a) A tile is picked up from a feeder and brought aside towards the mortar bed.

(b) A tile is gripped and pushed through the feeder for to the mortar bed.

Figure 7.6: The pick up or push down of just gripped tile.



(a) Specification in x-direction. **(b)** Specification in z-direction.

Figure 7.7: Acceleration, velocity and position reference profiles of the gripper.

7.5 Trajectory of the Placement Head

The motion path of the chosen configuration (Figure 7.6b) is the result of two reference profiles, specified in x- and z-direction. Figure 7.7 shows the acceleration, velocity and position profiles of the motion in x and z.

The trajectory starts with the downwards gripping of a tile and the push through the feeding system. After that, the tile speeds up, to align with the floor from the moving robot. Existing tilework is approached with a decreasing joint width motion. Time is reserved for fine-alignment and gently lowering the tile for setting in the bond coat, during a constant motion of 150 mm/s in opposite x-direction. Lastly, vacuum is released and the gripper quickly moves back.

Note that this trajectory may slightly vary for each tile placement, due to the closed loop positioning in x-direction. The trajectory furthermore indicates an arbitrary travel in z-direction. This should be as small as possible, but sufficient to push a tile through to feeding system to within a few millimetre above the mortar bed.

7.6 Downstroke z

The downstroke of the gripper faces big forces. It should be stiff to prevent deflections during placement. The placement device ought to bring the tile to a fixed position, rather than applying a fixed force to the tile.

Despite the latter, reaction forces as a result of pushing the tile in the bond coat should not excessively exceed the levelling capabilities of the electro-mechanical actuators of the suspension. When this occurs, the position of the robot body is highly disturbed which takes time to recover. Some kind of exceeding-force protection is preferably incorporated in the z-stroke design.

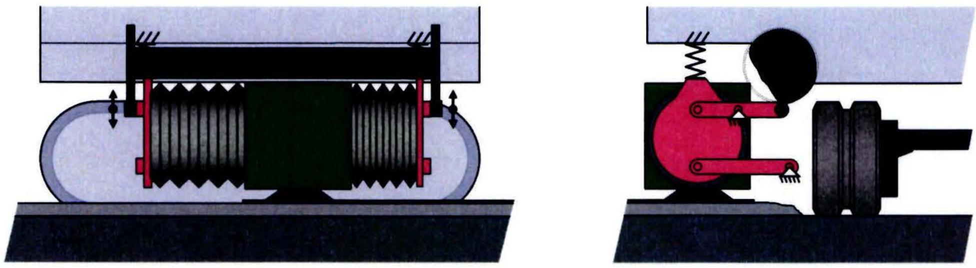
The actuation of the placement stroke can either be before or after the horizontal stage. Two concepts are shown in Figure 7.8.

In Figure 7.8a, the downstroke actuation is before the horizontal stage. A camshaft raises the horizontal stage assembly where the maximum placement force is adjustable by the tension springs. The placement head can be light-weight and enough space is available to create a stiff structure in all other DOF's, apart from z.

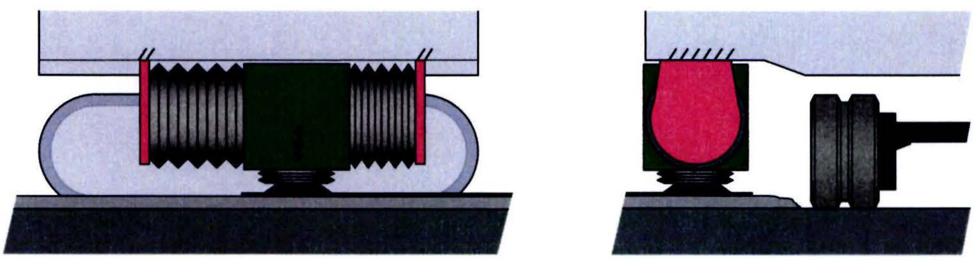
Figure 7.8b features a z-travel in the placement head. It results in a heavier mass to be moved in the faster x-direction. However, as the z-moving mass is smaller, disturbance forces on the levelled robot body are less. As there is less construction space available, it is more challenging to create a rigid and straight z-stroke mechanism.

7.6.1 Pneumatic Diaphragm Actuator

A pneumatic diaphragm actuator offers a high force for a limited stroke in a small and light design. It also has the property that the actuation force has a limit, resulting from the applied pressure in the cylinder.

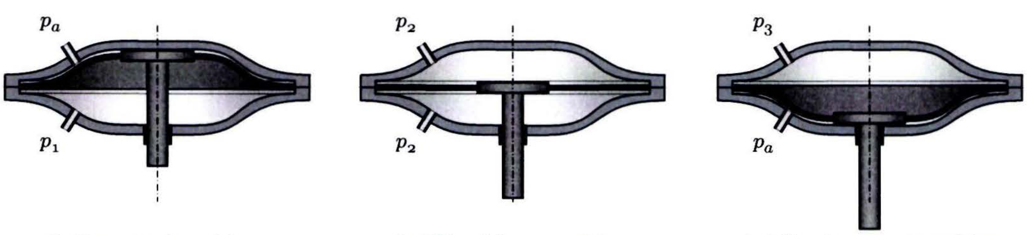


(a) The complete placement device is translated, enforced by cams.



(b) A z-stage is incorporated in the placement head.

Figure 7.8: Two distinctive concept designs for the z-stroke of the tile placement device.



1. Retracted position. **2.** Tile pick-up position. **3.** Tile placement position.

Figure 7.9: Working principle of a diaphragm actuator performing a z-stroke in the tile placement device.

Figure 7.9 shows the working principle of a pneumatic diaphragm actuator. The retracted position (1) is applied during the return of the gripper to the tile pick up position. Next, by releasing pressure p_1 in (2), the whiffletrees and suction cup make contact with the tile and release one from the feeder. Lastly, the actual tile placement is performed by applying pressure p_3 to the top chamber (3).

With the use of a diaphragm cylinder for the z-stroke design, impact forces at tile pick-up are low, compared to the external z-stroke design with a camshaft. The maximum force F_b at the impact of the gripper with the tile can be described by

$$F_b = v_b \sqrt{m \cdot c}\ .$$

Here, m contains the mass of the membrane and whiffletrees, c is the compound stiffness of the structure with mainly the membrane stiffness, and v_b is the approaching velocity. The latter can be adjusted with the speed of releasing air. For stiffness c, a compromise has to be found as the bouncing amplitude u_b is more for a compliant design, which can be described by

$$u_b = v_b\sqrt{\frac{m}{c}} .$$

Stiffness during tile pick-up can be increased by raising pressure p_2 on both sides of the membrane. For a gentile and reproducible pick-up of tiles, impact forces and bouncing amplitudes should be kept to a minimum.

7.7 Design of the Reciprocal x-Stage

The tile placement head is subjected to perform a reciprocal motion in x-direction. From Figure 7.7, it is concluded that its stroke is approximately 230 mm with the specified trajectory. A stage with a bit longer stroke allows a variation of trajectories, also essential to align tiles. A stage over the full length of the tiling robot has the advantage that it can tile closer to the wall at the beginning and end of a tile row; however, this is not necessarily needed as the mortar robot is not able to tile to the wall either.

Under the controlled x-motion of the placement head, the stage should withstand the large placement force (supposed to be 1500 N), and support it to the body of the robot. The use of track wheels or rollers in the design of a linear stage yield almost frictionless motion and enables positioning, free of hysteresis. A sufficient number of rolling elements and a correct use of them, can bear large forces.

Protection or resistance to cement dust is another important issue in the design of the stage. As rotational joints are easier to seal than linear stages, link mechanisms are considered, attaining an (approximate) straight-line motion. Linkages with elastic hinges do not require sealing at all, however the realisation of a stiff hinge with large deflection angle is limited.

Figure 7.10 shows two applicable linkage mechanisms, attaining an approximate straight-line motion of the red link, which moreover stays (approximately) horizontal. The red link is a representation of the placement head. A lateral guidance of the placement head can be obtained by a similar mechanism.

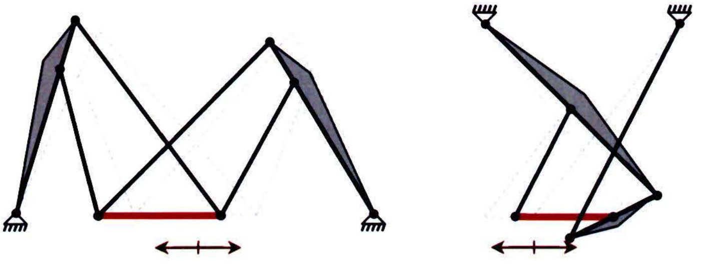


Figure 7.10: The double luffing-crane mechanism (left) and the extended Chebyshev linkage (right) attained approximate straight lines [CPS07].

Both the double luffing-crane mechanism and the extended Chebyshev linkage produces an approximate straight line. A better straight line can be obtained by scaling up the mechanism, and this means that less or possibly no correction is needed of the suspended robot body.

A light but stiff linkage is essential for a fast movement. The linkage should bear the large placement force without excessive deflection. However, because of a desired light-weight and inevitable tall design, stiffness is limited.

After all, because of the non-straight motion and limited stiffness properties of the examined linkage mechanisms, a linear stage design is chosen, consisting of a carriage with track rollers, running over a straight and stiff guideway, and yet completely sealed by two bellows on each side of the moving carriage.

R&K Techniek [RKT] offers an elastic PVC bellows with outer diameter $D_o = 275$ mm and inner diameter $D_i = 220$ mm. All critical components such as guideways, actuation components and preferably also cables should fit in the bellows's inner passage.

As the cylindrical bellows completely cover the rail, the rail can only be mounted to the robot's body on both ends. A bending and torsional stiff rail design is required.

7.7.1 Design of the Carriage

Figure 7.11 shows the use and position of track rollers on a carriage. Four rollers on the underside of the guideway (red) determine the z, φ, ψ-position of the tile. The tile aligns to the guideway surface which must be sufficiently straight.

Because the reaction force of placement (pointing upwards) will be larger than the weight of the carriage, the four fixed rollers are placed underneath the guideway.

The carriage deadweight is supported by four preload rollers on the upperside of the guideway (blue).

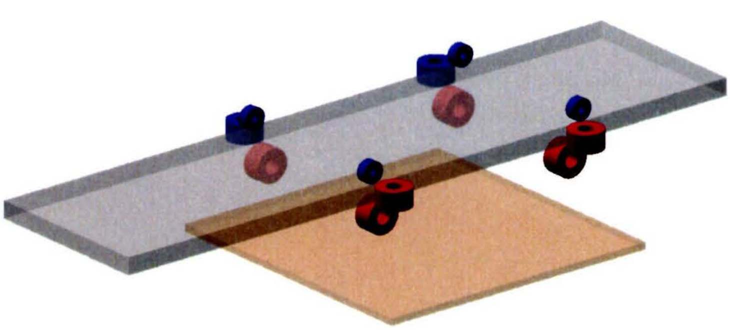


Figure 7.11: Six fixed rollers (red) and six preload rollers (blue) with a 300 mm × 300 mm tile for comparison.

Together with a tile, the carriage is aligned to the track in y and θ by two rollers on the side (red). Two rollers on the other side (blue), hold the carriage on the guideway and preload the red rollers. The preload force should be larger than the maximum lateral force that can act on the carriage during tile placement.

Preload rollers reduce the load bearing capacity to one side, but gives a higher initial contact stiffness. It furthermore has the advantage of eliminating play and slip of rollers, enhancing service lifetime. Variations in the guideway's width and thickness are absorbed in the preload spring movement, as well as sand or cement unintentionally obstructing the smooth runway.

Rollers are selected with a curvature on the running surface of 500 mm radius. This allow small tilting misalignments of the rollers with the mating track and avoids edge stresses.

7.7.2 Design of the Linear Guideway

Track rollers ought to run on straight, high-grade steel runway. One big steel strip is chosen to be the runway for all rollers. A finish-ground strip of cold-worked tool steel (90MnCrV8) with dimensions $l \times w \times t$ = 1000 mm × 180 $^{+0.20}_{-0.00}$ mm × 18 $^{+0.05}_{-0.00}$ mm is selected from Hersbach [Her].

Featuring a stroke of 300 mm, carriage length of 280 mm and two times the length of a folded bellows of 60 mm, the strip is cut to a length of 700 mm.

The bending and torsional stiffness of the strip is increased by mounting it to an U-shaped hood, folded from sheet metal. The strip should be bolted to the hood, which makes the strip exchangeable when worn out. Figure 7.12 shows the guideway assembly design, together with the position of the rollers.

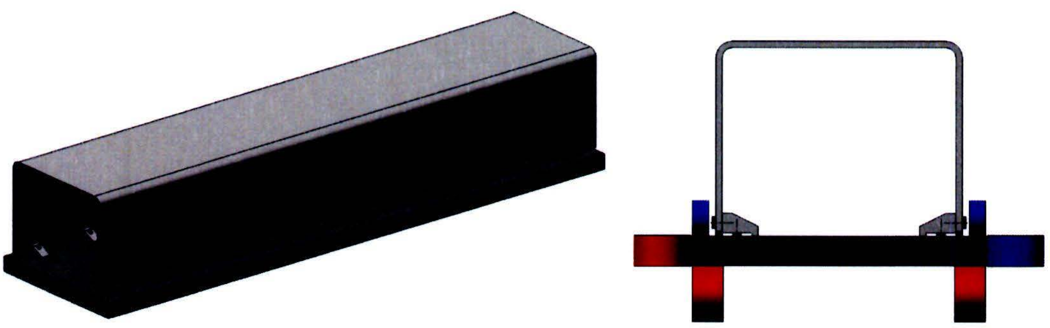


Figure 7.12: Guideway design.

To minimise bending moments on the strip, the centre line of the folded plate should lie closed to the centre line of the fixed rollers.

The high in-plane stiffness of the vertical plates of the U-profile makes the guideway stiff against bending. The U-profile mounted on the strip yields a hollow section with a closed contour, which makes the guideway torsionally stiff.

7.7.3 Actuation of the Linear Stage

A linear ball screw is chosen for the actuation of the carriage on the rail. The threaded shaft is placed inside the bellows for protection against water and dust. To drive the carriage in line with (or close to) the COG of the placement head, the ball screw is intended to be underneath the runway, on the stage's vertical centre line.

Figure 7.13 shows the linear rail and ball screw, fitted just inside the bellows seals.

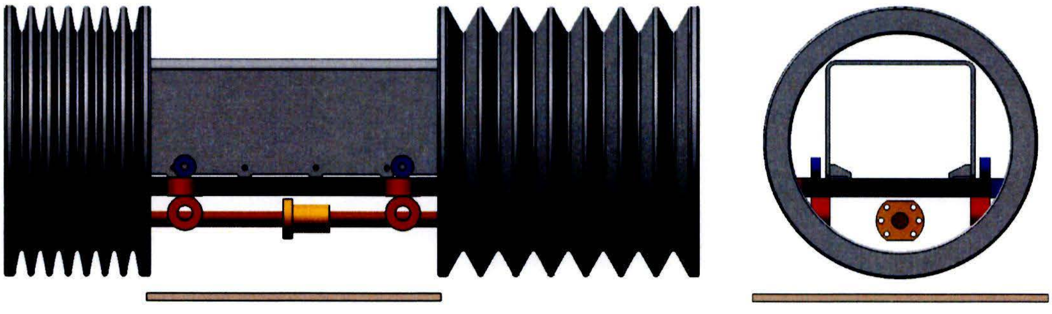


Figure 7.13: Guideway assembly.

7.8 Partial Design of the Placement Device

A tile placement device design is presented of which several components are elaborated. The tile placement device design consists of a stacked x-stage and z-stage. The bending and torsionally stiff guideway, part of the x-stage, is mounted on the suspended tiling robot body. A carriage with track rollers runs over the guideway, driven by a linear ball screw assembly. The complete x-stage is protected from the environment with bellows seals.

Tiles are gripped with a suction cup on a six-point support with whiffletrees and via a pick-up and push-through sequence, brought to the mortar bed. To perform the z-positioning stroke and to apply the placement force, a pneumatic diaphragm actuator is suggested.

A sealed, light and stiff assembly of the placement head carriage should be designed further, featuring the suction cup, whiffletrees, diaphragm cylinder, fixed and tension rollers, screw nut connection and bellows seal.

Chapter 8

Conclusions and Recommendations

In the foregoing, a study is presented on automated tiling, accompanied with a conceptual design. Next, conclusions are drawn and recommendations are made.

8.1 Conclusions

This project is aimed to ease labour of tilers by means of mechanical assistance. To the best knowledge, no equipment on automated tiling is commercially available, though there have been some research projects in the past.

A solution is found on automated tiling of rough construction floors of middle to large size; for example supermarkets, airport terminals or swimming pools. A mortar robot applies strips of mortar on the floor and a tiling robot applies tiles to the mortar strips, row by row. Operators will set up references for the robots, load them with tiles, mortar and bond coat adhesives, and manoeuvre and initiate the robots for a new row.

From a brief cost-effectiveness study, a desired speed of tiling is set at 2 seconds per tile. The permissable tile placement accuracies are found to be in (sub)millimetre range. To fix a tile, a bonding method using cement paste is found appropriate where a static assembly force between 0.4 to 1.5 kN is experienced to be sufficient.

As ceramic tiles can have large dimensional variations, its geometrical centre is considered and aligned to an imaginary grid on the floor. The average plane of a tile's surface is searched by a six-point support gripper with whiffletrees. To avoid repetitive patterns in the tiled floor, one tile is placed at a time.

Of the several measurement systems that are examined, a system is drawn up consisting of lasers and tilt sensors, able to provide the robot with submillimetre feedback on its position and angular orientation. With the selection of commercial construction laser equipment, a feasible, robust and easy-to-use solution is found.

The presented tiling robot design features an actively controlled body, suspended on air springs. Static stability is analysed and the robot is safe from tipping over. The dynamical behaviour shows a good isolation of vibrations, provided that an adequate controller is implemented. A two-dimensional dynamical model is available for optimising suspension design and simulating controller design.

The initiated design of the linear tile placement stage features a replaceable, stiff and straight guideway, protected from cement dust and water, where track rollers keep the tile aligned to the guideway.

A technical feasible solution for assisted tiling is created in the presented robot design with complementing measurement system. An impression of the setup is shown in Figure 8.1. Among others, the design features a good fixation of tiles, accurate alignment of tiles, economical feasibility, operation in a rough environment with water and cement dust, integration with other construction site machinery. Provided there is market potential, further development is encouraged towards a commercially applicable tiling robot.

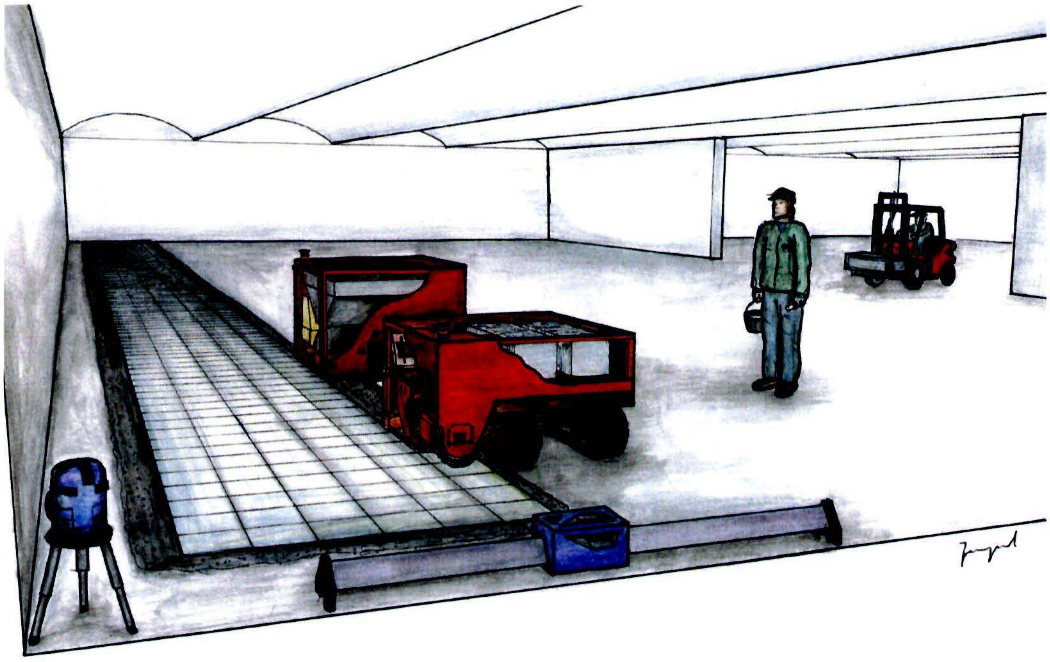


Figure 8.1: Design impression of the robotic system, tiling a rough floor while guided by the laser measurement setup.

8.2 Recommendations

This report focusses on the technical feasibility of robotic tiling. Though a brief cost-effectiveness case is presented, it is advised to perform an economical feasibility study on robotic tiling and conduct market research under tiling companies for their preferences and experiences, and willingness to participate in further development. A prototype is best to be developed in close corporation with industrial partners.

The presented design is suitable for tiling rough floor with thick-bed mortar. Yet, with minor modifications, it is possible to apply tiles on flat surfaces with thin-set adhesive, deploying only the tiling robot. Further research is required whether it is possible and favourable to give also this functionality to the tiling robot.

Furthermore, only 300 mm square tiles are intended to be laid by the robot. The ability to handle a variety of dimensions should be reviewed for a commercially tiling robot design.

By means of conducted experiments on tile embedment, FEM simulations and basic feelings, a method of tile placement is made-up and a gripping device is designed. As a proceeding step, it is encouraged to build a gripper prototype and conduct experiments with real cement, to evaluate the applied method of installation and improve the gripper design.

The presented measurement system of lasers have some limitations but also some possibilities for further development. When working out the laser guidance system, these aspects should be considered.

A start is made on the design of the tile placement device. This should be continued. Furthermore, a configuration of air springs is proposed as the bodywork suspension. Further research is required to find the best configuration and mounting of air springs and electro-mechanical actuators. Simulations with the presented dynamical model can give a help.

The rubber track undercarriage faces unequal load and wear. Ideally, this effect is to be diminished. Furthermore, the number of tiles that can be loaded on the robot is limited by the weight limit of the undercarriage. It may be beneficial to consider using a bigger undercarriage or lightweight design.

Appendix A

Experiments and Measurements

A.1 Tile Bonding

At the Eindhoven ROC tiling educational centre (Figure A.1), experiments were conducted on the procedure of tiling, the degree of tile fixation and tile deviation. The experiments were performed while accompanied by tiling instructor Jan Feijen from ROC.

Figure A.1: ROC tiling department with an experiment going on in foreground.

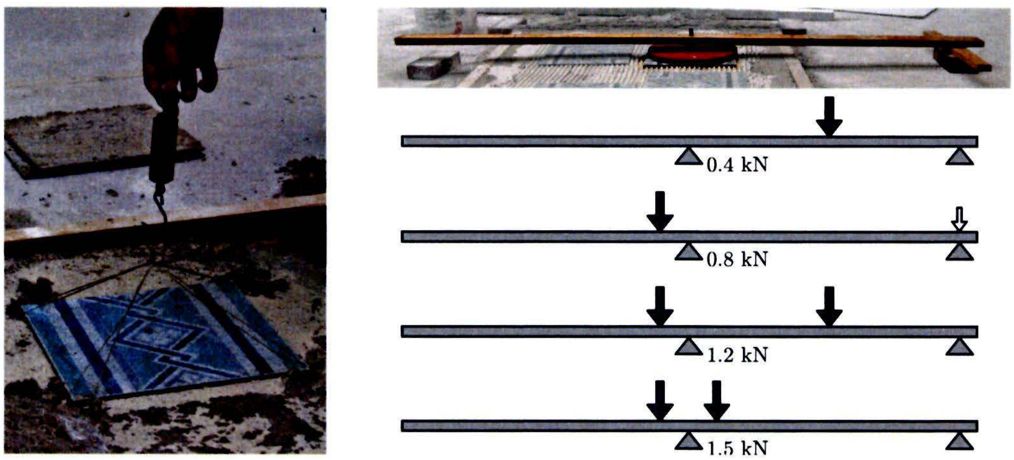
A.1.1 Test Conditions

In stead of cement, lime is used at ROC. This is because of the reusability of mixed lime mortar. Lime forms a sticky solution when dissolved in water but does not cure. Lime also has been used in the experiments. Though lime mortar is very comparable in terms of consistency and workability to cement mortar, there might be some differences.

A.1.2 Method of Testing

For evaluating embedment, each installed tile is pulled off the mortar bed with a moderate slow upwards motion. Meanwhile, the pull off force is measured with a spring scale, as depicted in Figure A.2a. The stated values are rather inaccurate and should be read with a tolerance of ± 10 N.

Applying a static assembly force is realised using body weight. Two persons, each having a mass of 80 kg, are to be standing cautiously on a bridge construction according to Figure A.2b to create the desired assembly force. The bridge is connected via a ball joint (to unconstrain tilt) and a pressure distribution plate to the tile.



(a) Spring balance. (b) Build up of assembly force.

Figure A.2: Tools for experiments.

A.1.3 Embedment at Static Force and Cement Powder Bond Coat

An experiment is conducted, whether a static assembly force can give a full embedment and good fixation of 300 mm × 300 mm tiles to the mortar bed with a cement powder bond coat in between; and to establish what magnitude is needed. The cement powder bond coat is made by sprinkling the compact mortar bed with water and dry cement powder. After the cement absorbs water, a sticky cement slurry is formed.

Figure A.3 shows the embedment of four sample tiles, installed with a force of 0.4, 0.8, 1.2 and 1.5 kN. The force, needed to pull the tile off is 40, 40, 40 and 50 N, respectively. The backsides of the tiles reveal bad fixations, regardless of the magnitude of the assembly force.

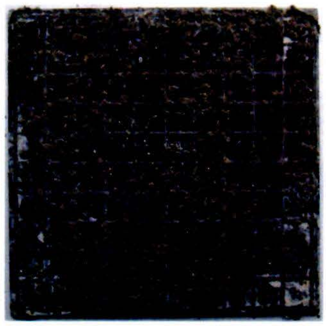
A.1.4 Necessity of Water-Absorbed Cement

The manual tiling method is to apply the bond coat and wait for about 10 minutes to let the cement absorb the water and to let the coat stick to the mortar bed top surface. In robot design, this time span is not practicable.

(a) Assembly force: 0.4 kN.

(b) Assembly force: 0.8 kN.

(c) Assembly force: 1.2 kN.



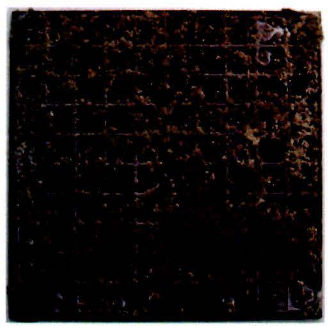
(d) Assembly force: 1.5 kN.

Figure A.3: Embedment of tiles, installed on a cement powder bond coat, with a varying static assembly force.

In Figure A.4, the necessity of this absorbing time is investigated. Apart from a normal procedure (Figure A.4a), the tile of Figure A.4b is installed immediate – that is as quickly as possible – after strewing out dry cement. The tile of Figure A.4c is immediately installed too, but has a wetted backside as this might promote adherence.

(a) Normal installation.

(b) Immediate installation.



(c) Wetted backside.

Figure A.4: Embedment of tiles, installed on a cement powder bond coat, under varying bond coat conditions.

Each tile is installed on a cement powder bond coat and installed with a reference assembly force of 0.8 kN. To give time for absorbtion when the tile is installed (in practice unlimited) the tiles are pulled off about 10 minutes after installation and examined. Though there is some difference in embedment and pull off force (60 N, 40 N, 60 N, respectively), it is not that decisive such that placing with a dry cement bond coat is made possible.

A.1.5 Compacting by Rolling or Beating

A difference in tile embedment is visible in the tests of Figure A.5. The tiles on the right are placed on a bed which is compacted in a different way than slapping it with a trowel, namely by rolling the bed with a 0.25 kN down force on the roller (Ø = 100 mm, l = 600 mm). Consider Figure A.6.

As the mortar bed is a bit more compressible, it is able to contact the tile's back better. However, note that this might not necessarily mean the tiles have a better fixation to the floor. As the mortar bed is less or differently compacted, it can thus be the weakest link when pulling off.

(a) Beaten mortar; rubber hammer

(b) Rolled mortar; rubber hammer

(c) Beaten mortar; 0.8 kN static

(d) Rolled mortar; 0.8 kN static

Figure A.5: Embedment of tiles, installed on either a rolled or beaten mortar bed, with either a rubber hammer or a static force of 0.8 kN.

(a) Beating the mortar bed **(b)** Rolling the mortar bed

Figure A.6: Two ways of preparing the mortar bed.

A.1.6 Compression of Bond Coat

The compression of bond coats is measured using four dial indicators mounted on a frame around a tile to be measured. See Figure A.7.

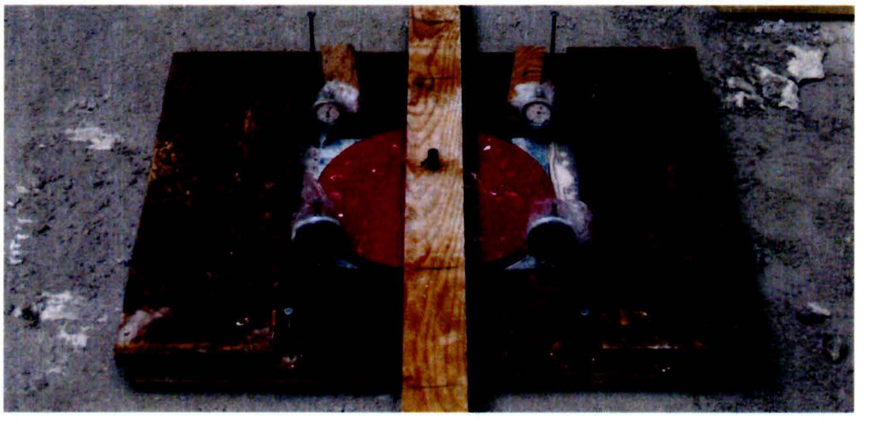


Figure A.7: Device for measuring bond coat compression.

A total of four tiles are examined; two for each bonding method. The measured compression is relative to the initial position (denoted with 0.0 kN in the graphs). This initial position is equal to a tile slowly laid on the prepared mortar bed. This is however very arbitrary as the mortar bed and bond coat have a rough top surface finish and are likely to be inhomogeneous.

Figure A.8 depicts the average downwards compression of the tiles and the tilt deviation in both directions. Load is applied to the tiles up to 1.5 kN in successive steps of 0.4 kN. Though the angle is left unconstrained, the angular deviations can be partially caused by lateral forces during the application of the load.

For the tiles placed on the paste bond coat, a visco-elastic effect was observed when applying the assembly force. Also after releasing the assembly force, the tile gradually moves back. (For an assembly force of 1.5 kN the spring back is about 0.05 mm with an estimated 3τ time constant of 2 s).

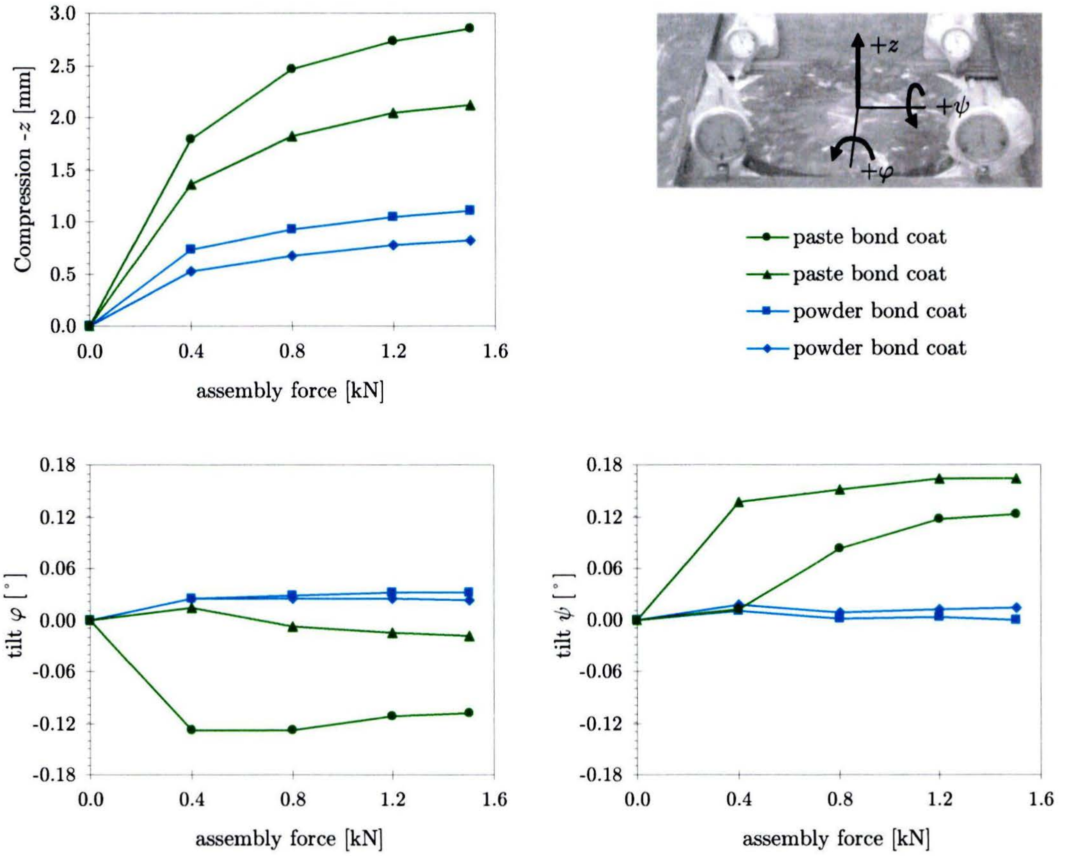


Figure A.8: Measured tile compression and tilting.

A.2 Mortar Properties

Mortar used for thick-bed tiling is made from 4 parts river sand and 1 part Portland cement. Next, water is added such that the correct workability is achieved. In literature, this is denoted with the water/cement mass ratio. A quick test for evaluating the proper moisture level is by taking a handful of mortar and squeeze it in the hand. See Figure A.9. If the mortar feels powdery and falls back into pieces after squeezing, it is too dry. If it is moldable and remains its shape, it has the right consistency. If it feels plastic and leave traces of moisture on the fingers, it is too wet.

Figure A.9: Hand test to evaluate moisture level of mortar.

A.3 Tile Properties

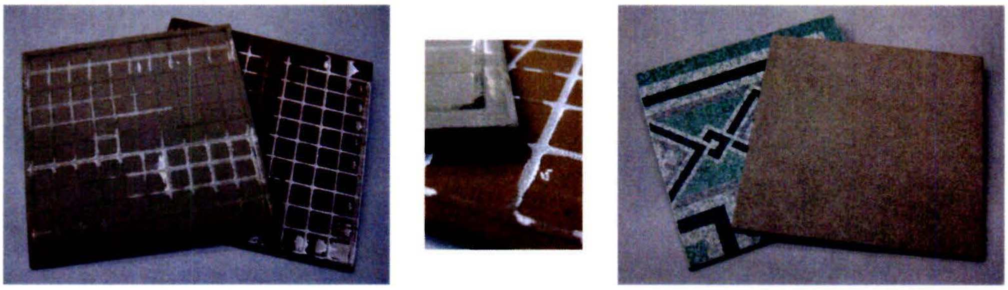


Figure A.10: Two tiles taken as an example within this project.

Table A.1 listed some properties of a sample ceramic floor tile from Mosa. It is the white blank tile of Figure A.10. Note that the printed requirements on bending strength is prescribed by Mosa. Norm EN-14411 specifies a bending strength of 25 MPa.

nominal dimensions	300 mm × 300 mm
actual dimensions	297 mm × 297 mm
mean thickness	7.6 mm
weight	1.57 kg
density	2340 kg/m^3
Possion's ratio (assumed)	0.3
Young's modulus (see below)	74 GPa
bending strength	40 MPa

Table A.1: Sample tile properties.

A.3.1 Tile Young's Modulus

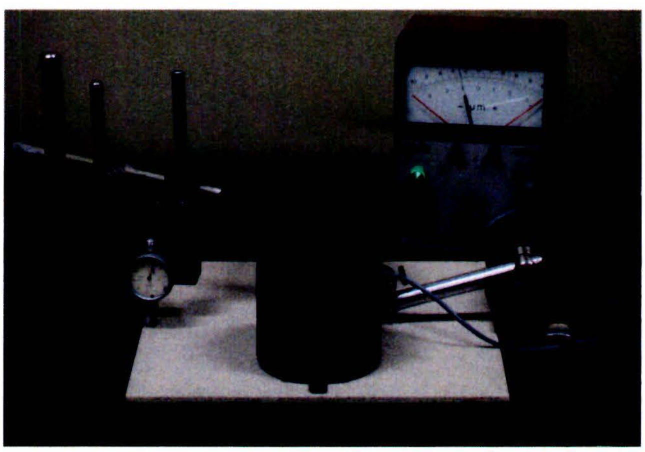


Figure A.11: Setup for determining the tiles Young's modulus.

The Mosa tile is examined in a bending test with the setup as depicted in Figure A.11. The bending deflection is determined under load. The Young's modulus is calculated by

$$E = \frac{F\, l^3}{4\, \delta x\, b\, h^3} \tag{A.1}$$

where F is the applied load with corresponding maximum deflection δx, l is the distance between the supports and b and h are the width and average thickness of the tile, respectively. The Young's modulus is found to be 74 GPa.

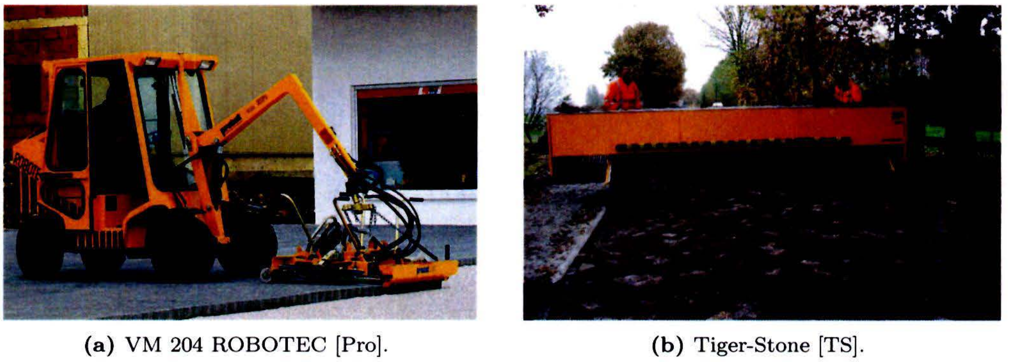
Appendix B

Commercial Machinery

This appendix lists some machinery used for, or related to, tiling. The state of automation in the related paving industry is discussed; machinery for mortar preparing and grouting are listed and data of the OEM undercarriage used, is included.

B.1 Machine Laid Paving

Two examples of block paving machines are depicted in Figure B.1. The machine of Figure B.1a picks up an arranged pattern of blocks or tiles by clamping or by vacuum pads and places it at once; that of Figure B.1b slides a slab of blocks on the road, laid by workers in standing posture.



(a) VM 204 ROBOTEC [Pro]. **(b)** Tiger-Stone [TS].

Figure B.1: Two examples of commercial block paving machines.

Figure B.2 shows an automated block paving robot [ST1]. It is aimed to have a more autonomous and multi-functional paving robot. Hence, it is equipped with a robotic arm, GPS system and vision cameras. It is able to place 1200 blocks per hour and has a placement accuracy in millimetre range. The patented design did however not result in a commercial machine.

Figure B.2: The StreetWise 1200 block paving robot. [ST1, OBN]

B.2 Mortar Machinery

B.2.1 Compressed Air Conveyors

For mixing mortar or screed from dry components and delivering it to the subjected floor area, a compressed air conveyor is used by flooring companies. An example of such a machine is the Estrich Boy 550 from Brinkmann Maschinenfabrik [Est]. A diesel engine, compressor and mixing vessel are on-board. Figure B.4 shows the working principle of the mixing vessel of 200 L. Sand and cement are loaded with water in the mixing vessel and the lid is closed for mixing. After that, compressed air at 7 bar pushes clods of mortar in short bursts through the delivery hose to its delivery destination. A mortar delivery performance of 3.7 m^3/h is reported for the electric-powered version [Est].

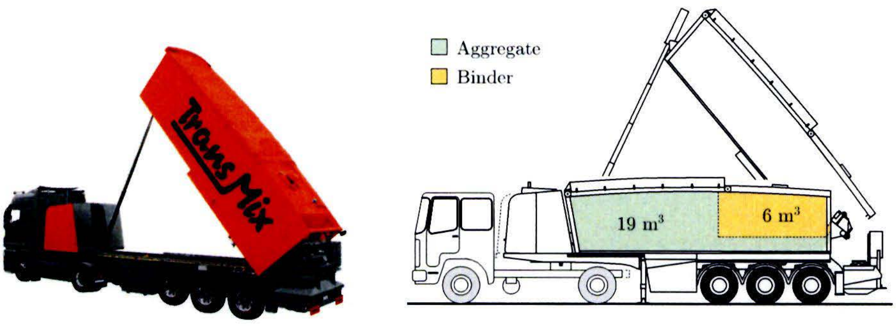


Figure B.3: Trans Mix 5500 [Tra].

B.2.2 Trans Mix

Other equipment for processing cement screeds are mobile logistics systems. For example the Trans Mix tiltable semi-trailer from Brinkmann Maschinenfabrik [Tra]. All elements of the compressed air conveyor are present; the same mixing vessel and pump is installed. Besides that, Trans Mix equipment has separate compartments for aggregate (sand) and binder (cement), providing transport to the construction site. Furthermore, it has a fully automatic production cycle such that no workers are needed to load the mixing vessel. The machine operator has a remote control to adjust the desired supply rate.

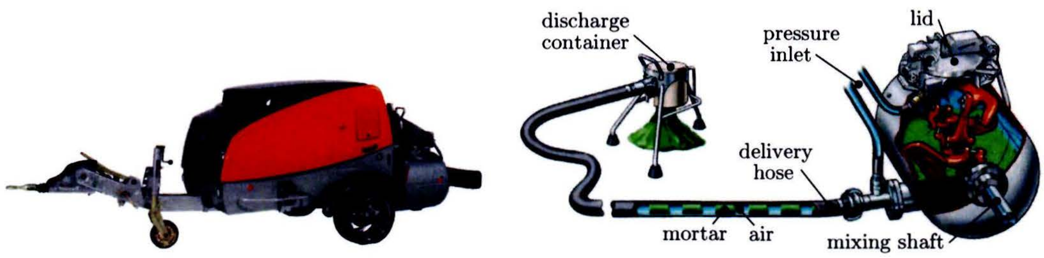


Figure B.4: Estrich Boy 550 [Est].

B.3 Grouting Machinery

B.3.1 Grouting Machine

For the job of grouting a tile work, several machines exist. Figure B.5 shows two different examples of grouting tools. Grout is applied to the floor to fill the tile joints. The excess is wiped away with a circulating or translating motion.

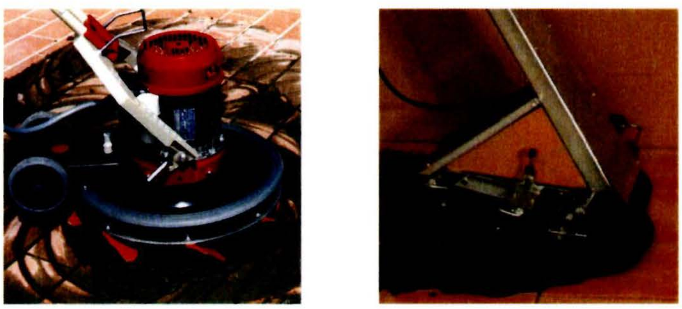


Figure B.5: Two examples of grouting tools: Raimondi Maxititina (left) and Tileze 750 (right). [Rai], [Til]

B.3.2 Grout Cleaning Machine

The haze of grout left on the tiles, can be removed with a grout cleaner. Figure B.6 shows two machines having a continuous sponge wiping the floor and wringed out in a water container.

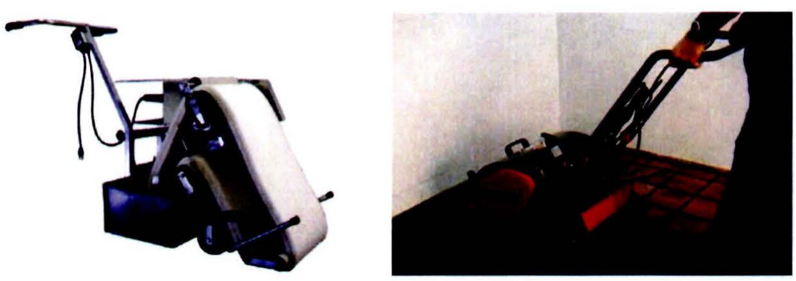


Figure B.6: Two examples of grout cleaning tools: Tileze 6000 (left) and Rubi Spomatic (right). [Til], [Rub]

B.4 Hinowa Undercarriage

The undercarriage depicted in Figure B.7 and B.8 is used in the robot's design.

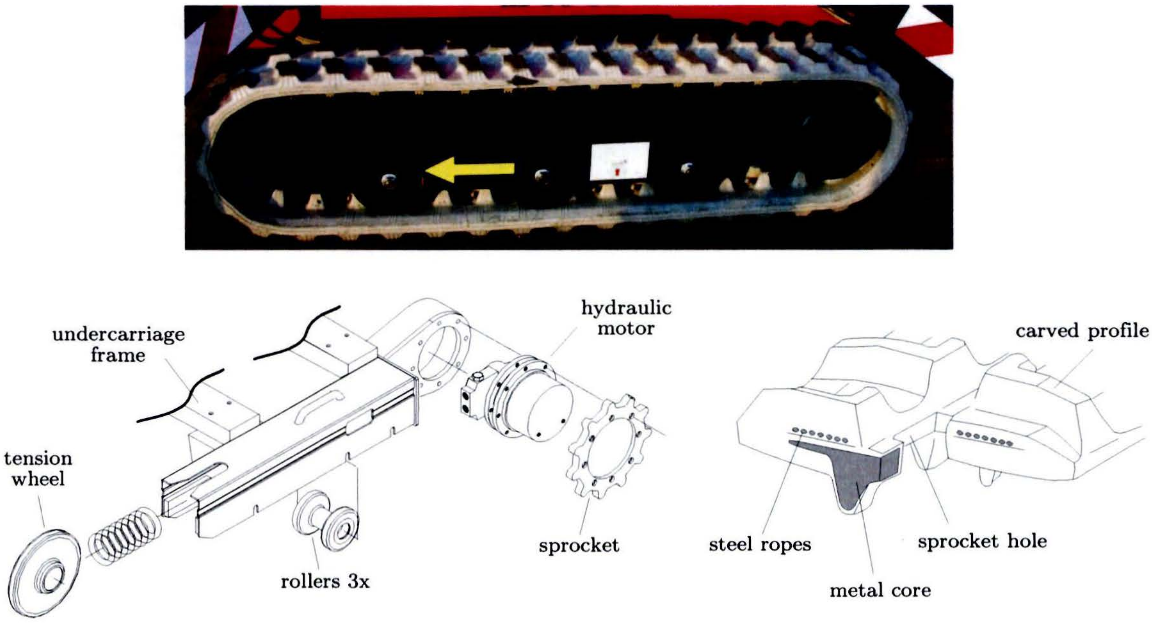


Figure B.7: Some pictures of the Hinowa PT9CG undercarriage [Hin].

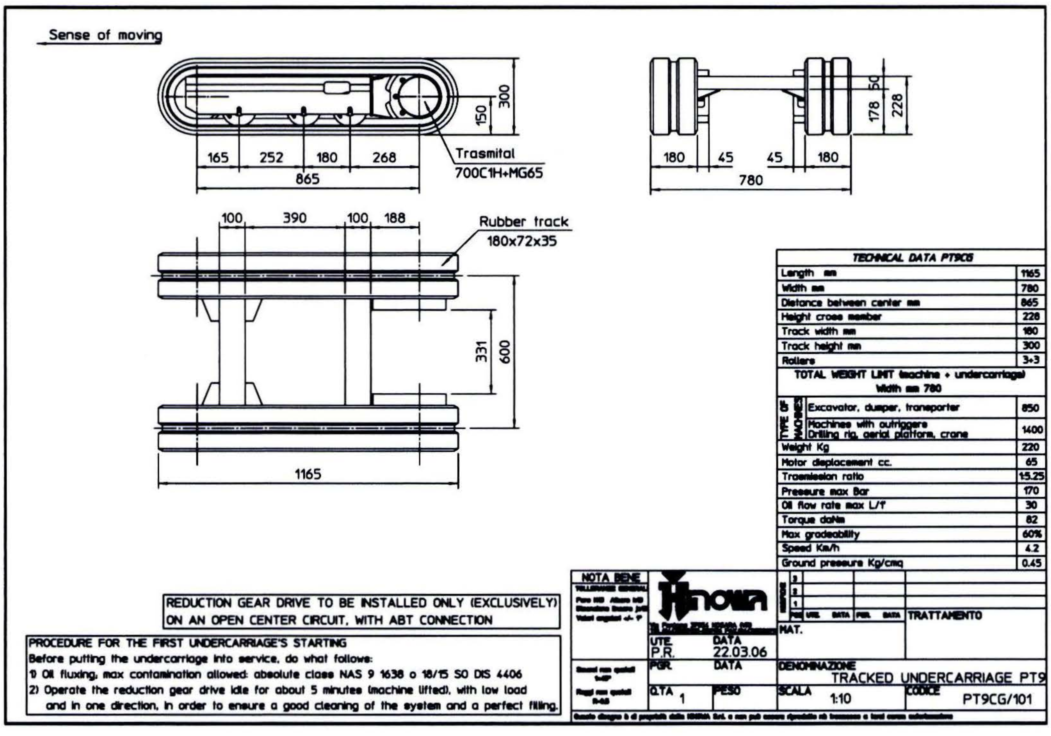


Figure B.8: Data sheet of the Hinowa PT9CG undercarriage [Hin].

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