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Line inspection robot

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Abstract The line inspection robot autonomously inspects power lines while mounted on a live phase-line. The project to develop the line inspection robot is an initiative from ABB Corporate Research in Västerås, in collaboration with Uppsala University. Previous solutions to the line inspection problem are presented. The line inspection robot is described and analyzed. Focus is placed on mechanical design and many details are given on individual design choices and their motivation. A basic market survey and an estimation of the value of a line inspection robot are supplied.	
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Line inspection robot

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Sammanfattning

I Sverige finns 30000 km kraftledning med en spänning på 130 kV eller mer. Alla dessa större kraftledningar måste inspekteras varje år, eftersom de är så viktiga för elnätet och därmed för samhället. Inspektionen sker idag från marken eller från luften, det är ett repetitivt och farligt arbete och därför väl lämpat för automatisering. I det här examensarbetet utvecklades en klättrande, autonom robot för inspektion av strömförande kraftledningar.

Roboten placeras på en strömförande kraftledning, på vilken den hänger i två hjulpar. Från denna position kan roboten färdas längs med kraftledningen i endera riktningen. De största svårigheterna under inspektionen är att klättra förbi hinder på kraftledningen och att avgöra när det är fel på ledningen. Examensarbetet har resulterat i en prototyp som vidareutvecklas i en projektkurs vid IT-institutionen vid Uppsala universitet i samarbete med ABB Corporate Research.

Examensarbete 20 p i Molekylär bioteknikprogrammet

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PREFACE

This report treats the previously little or un-explored area of line inspection robotics. The kinematics and practical limitations of robots able to climb on live power lines are mostly unknown. It is my hope, as the author, that the analyses and conclusions presented in this report are correct and that it will expand the knowledge in the field.

Design is an endeavour in dealing with the unknown. As engineers we collect all and any information we can find in an area, we make our simulations and base our assumptions on the best knowledge available to us. Then we take our, hopefully well calculated, risk. The solution presented in this report is the best available design for a prototype line inspection robot available to the author of this report when writing these words.

Torkel Danielsson

Uppsala, 12 February 2006

CONTENT

1 INTRODUCTION

This pre-study report presents the results of a thesis work. In the thesis work the line inspection robot, a potential robotic solution to the power line inspection problem, was explored and developed.

1.1 Overview

This report follows the same time-flow as the thesis work. First, the problem of power line inspection is expanded and defined. This is followed by a look at current techniques for solving the problem and a quick look at the proposed novel method of the line inspection robot.

Three surveys were conducted; a literature survey, a patent survey and a market survey. These are presented and the results analyzed.

The last section of this report focuses on the actual line inspection robot, its principle of operation and its mechanical design. Here is also presented a quick look at the future of the project and a detailed requirement specification for the first prototype.

1.2 Pictures and figures

All figures and pictures present in this report are made by or taken by the author, or are public domain material, or are used with permission from Svenska Kraftnät, unless otherwise stated in the captions.

2 THE POWER LINE INSPECTION PROBLEM

Power lines are everywhere. Over the past hundred years, electricity has become a part of our daily life and something most of us take for granted. To supply us with electricity, there is a need for a well developed power infrastructure. Electric power needs to be generated, transmitted and distributed.

Much of the power infrastructure is now nearing its end of life. In places, structures originally built in the 1920's and 1930's are still in operation. Power transmission equipment and apparatus is generally counted as having an active service life of 50 years. The main investments in the current power transmission infrastructure were made in the 40's and 60's, and are thus bound for replacement.

2.1 Maintenance of the power infrastructure

The ageing power infrastructure needs both continual maintenance and renewal. Transmission system operators (TSO) typically spend more time on renewing the transmission grid than they spend on the maintenance of it [1]. Renewal means that a whole line, or sections of it, is taken down for raw material reuse and new equipment is installed in its place. Maintenance is all activities which aim at prolonging the active life and good condition of equipment.

2.1.1 Maintenance activities

Maintenance activities fall into different categories:

- Tower maintenance
- Line maintenance
- Vegetation control

Out of these, vegetation control is by far the most common. Even in the Nordic countries, where vegetation grows slowly, there can be a need to control vegetation every third year [2]. In countries with a warmer climate, keeping the vegetation undergrowth out of dangerous proximity to the conductor can be an even greater concern.

Figure 1 Vegetation issues.

Line maintenance is needed whenever some part of the conductor or over-head ground wires is in need of repair. A typical item in need of maintenance is a damaged insulator. If an insulator is damaged or excessively dirty it can become conductive and cause flashover or other problems, in which case it should be promptly replaced [3].

2.2 Inspection

To perform effective maintenance and renewal of any equipment, there is a need to know the current status of that equipment. Power line infrastructure is no different. Before a TSO makes a decision about an investment they conduct studies to confirm the need of the investment [2].

Figure 2 Insulators in need of replacement.

Power line inspection is a multi-faceted problem. What is needed is information about the status of the power line, so a well founded decision can be made to perform maintenance, renewal or to do nothing. Obtaining this information is not a trivial task. Power lines are built in many different ways. There are different voltages which must comply with different standards. Even a TSO operating in a single country might have lots of different equipment in use. Between countries and continents, differences are even greater.

To inspect such equipment, the inspector needs to know exactly what the equipment looks like (or sounds like, or what readings a heat sensor should give, etc.) when it is in proper condition and when it is running a risk of failure (Figure 2).

2.2.1 Failing compression splices

Some equipment is notoriously difficult to inspect. An example is a compression splice running risk of failure. When two lengths of conductor are connected, a compression splice is used to hold them together. Compression splices sometimes fail, however, and when they do they need to be quickly repaired (Figure 3) or the whole line might fail. The resistance over a compression splice in good condition is lower than that over regular conductor of equal length. When the compression splice is failing this resistance is increased. The increased resistance result in heat in the splice, and the status of the splice deteriorates even further in a downward spiral. The current way to detect this is to either measure the resistance over the splice or to measure the temperature of the splice. Both are tricky things to do, considering the splice is on extreme voltage potential, high over ground and more often than not subject to winds that cool any temperature differences down to the immeasurable.

Figure 3 Replacement of failed splice (full-tension splicing of energized conductor).

2.2.2 Corona discharges

A corona discharge is “an electrical discharge brought on by the ionization of a fluid surrounding a conductor, which occurs when the potential gradient exceeds a certain value, in situations where sparking (also known as arcing) is not favored” [4].

In the context of power lines, corona formation is considered a very bad thing as it results in radio interference, ozone formation and equipment fatigue. Corona discharges are further associated with strange sounds and can even be visible at night time, resulting in public concern over power line safety.

Coronas form especially easy on protrusions from a conductor, where the electric field (potential gradient) is focused. Equipment designed for operation on live power lines needs to take this into account. Two, otherwise functionally identical, parts might cause or not cause corona discharges depending on the shape of extending edges. Smooth and round edges generally cause less corona issues [5]. Another cause of corona discharge formation is faulty equipment, see Figure 4.

Figure 4 Corona on failing 150 kV porcelain insulator.

Corona inspection has been the target of recent product development. Combining images from several camera types using advanced algorithms, it is possible to spot corona discharges in daylight. Cameras capable of this are available for purchase [6]. These cameras are used by a spotter on a helicopter or airplane.

3 EXISTING POWER LINE INSPECTION METHODS

Existing power line inspection can be divided into three separate categories; ground inspection, air inspection and automatic inspection. Out of these, ground and air inspection are by far the most common, but automatic inspection is regarded as the method with the best potential for the future.

3.1 Ground inspection

Ground inspection is the oldest and most intuitive power line inspection method. A crew of service personnel is sent out on the mission to inspect a power line. The personnel carry equipment to aid them in their task, but ultimately rely on their senses to perform the inspection. If the power line is close to roads or passable waterways, these are used. In places with heavy snow-fall, snowmobiles can be used. If no similarly convenient option is available, the service personnel have to traverse the length of the power line on foot.

Figure 5 Power line corridor with vegetation.

Following a power line on foot is not easy. Transmission lines often pass difficult terrain and are not built with convenient inspection in mind, see Figure 5.

3.1.1 Ground inspection techniques

Once under the power line, the service personnel must assess the status of it. The primary method of doing this is to visually asses the structures, using binoculars, cameras, or plain eyesight. Visual assessment is sufficient for most inspection of vegetation, insulators, towers and cables [2].

Certain power line faults, such as corona discharges, result in characteristic sounds. In these cases the ground crew can listen for the presence or absence of a fault. An antenna can be used to detect corona discharges, as they cause radio interference [5].

Infra red cameras or other sensors capable of remotely sensing temperature are used to find other faults, such as failing compression splices [7].

At times, the service personnel performing the ground inspection need to climb towers or even mount the actual line. Examples of this can be seen in Figure 6.

Figure 6 Service personnel working on energized lines.

3.2 Aerial inspection

Airborne surveillance is the next logical step after ground inspection. If visual surveillance suffices for the inspection needs, then a fly-over will be much more efficient than traversing the power line on foot. Airborne inspection is performed from helicopter or aircraft.

3.2.1 Airplane inspection

Airplanes have been used to inspect power lines for a long time. Pilots fly close over the line while an inspector, called spotter, sit next to them looking down at the line. Sometimes more than one spotter is used to look at different features of the equipment.

3.2.2 Helicopter inspection

Helicopter inspection is performed much the same way as airplane inspection, with one pilot and one or possibly more spotters; see Figure 7. The use of helicopters and airplanes for inspection differs somewhat, as helicopters are much less fuel efficient and come with a higher maintenance tag.

Figure 7 Helicopter inspection of power line.

Helicopters are used when their ability to hover is needed. Typically, this is when inspecting smaller lines or power lines in populated areas. When inspecting long stretches of high voltage power lines, airplanes are preferred [8].

One exception where helicopters are used on high voltage lines is in fault location. When a fault has brought a power line out of service, helicopters are used to locate the fault. The cause of a fault is often a tree or forestry equipment in contact with the conductor [2].

3.2.3 Recent development

Ongoing research strives to automate the aerial inspection process. Much attention is put to constructing video cameras that capture images of all equipment passed during a flyover [9]. Some systems are in operation today, and if they are improved they promise to decrease the cost and increase the quality of aerial inspection.

There is also long-term research in letting unmanned aerial vehicles (UAV) perform the inspection [10], but there are still many obstacles to overcome if this vision is to come true.

3.3 Automatic inspection

Automatic inspection of power lines is a collection of promising new methods for inspection. There are many possibilities to automate the inspection process. Current products focus on one inspection task and solve it by developing a specific product. One can, for example, order inspection of compression splices by a robotic inspection unit mounted under a helicopter [11].

As automatic power line inspection is a new and developing business it is hard to get a good overview of available technology and the quality of offered services. In this text a distinction will be made between fixed and mobile sensor systems.

3.3.1 Fixed sensor systems

A fixed sensor is mounted on the power line equipment and remains there through out its service life. Data from such a sensor is transmitted by cable or by RF-communication. The need for power in modern sensor systems can be made so tiny that a battery is sufficient for years of operation. Other power supply options in use today are solar cells, and equipment mounted on the conductor itself can through induction gather power from the varying magnetic field of the live line [12].

A fixed sensor system can answer many important questions for a TSO, such as how much current flow through a specific point of the line or the current conductor temperature at the same point.

Information provided by fixed sensor systems can have an impact on the operation of a power line. As an example, a sensor measuring the sag of a span of a power line gives indirect information about the distance to ground of that power line. Without measurements, this distance will be assumed to be worst-case. If a sensor provides actual numbers, a TSO can allow more current through the line. US patent 6523424 B1 describes such a device and its use in up-rating a power line.

3.3.2 Mobile sensor systems

In this text a mobile sensor system is broadly defined as any sensor which is not fixed to a power line structure. Examples of mobile sensor systems are UAV carrying sensors for power line inspection, or line-crawling robots for power line use.

The sensors in this category are more experimental in nature than the fixed sensor systems. Research in this field is ongoing, much of it funded by the power industry. With many published papers each year by several research groups, the future for power line inspection using mobile sensor systems looks bright and promising [13].

4 PROPOSED INSPECTION METHOD

This report proposes the line inspection robot as a solution to the power line inspection problem. The line inspection robot is a line-crawling autonomous robot, constituting a mobile sensor system.

The robot will be able to clear transmission towers and other reasonable obstacles. While traveling along the line it will carry sensors enabling it to perform most inspection activities performed today, and more. A key concept of the approach is the gathering of power from the live line, enabling the robot to inspect for long periods of time without being bothered with energy-supply issues.

This section will begin with demands on the robot, followed by a look at a use scenario of the system.

4.1 The line inspection robot

The robot forming the core of the line inspection robot mobile sensor system must comply with several demands for the system to be useful. The robot must:

- Travel along the conductor of a high voltage power line
- Pass pre-defined obstacles on the power line (i.e. all common obstacles)
- Capture enough power for robot’s use, from the magnetic field generated by the conductor (possibly storing power for intermittent operation)
- Inspect pre-defined features on the power line
- Communicate with a base station (or other unit of similar function)

The line inspection robot will be part of a system offering the inspection capability. The system must, at least, have the ability to:

Conveniently raise the robot to, and lower it from, the line to be inspected
Report, and provide some initial analysis of, the results of an inspection
Offer some way of communicating with the operating robot, perhaps offering some remote control abilities

The operating conditions close to a live conductor of a high voltage power line are extreme. The line inspection robot may not cause harm to people or equipment, specifically:

- It must not damage the conductor on which it travels
- It must not cause damage to insulators
- It must not cause flashovers between tower and conductor
- It must not cause flashovers between different phases
- It must not cause corona discharge

4.2 The project

This report describes the pre-study undertaken as the first step in the development of the line inspection robot. As the report progresses, more and more of the robot design will fall into place, ending with a final prototype design.

4.3 Use-scenario

This section describes the intended function of the line inspection robot, step by step, in a use-scenario. This analysis of the intended use of the robot system will hopefully be useful in specifying exactly what problem the system intends to solve, and to identify the difficulties which must be overcome in order to realize it.

4.3.1 Inspection cycle

The vision of the complete line inspection robot system is a system which is available for TSO use with little or no preparation. When an inspection need arises, the system is quickly programmed and the robot is transported out to the inspection site and raised to the line where it right away starts the inspection. This scenario step-by-step:

- Robot is in storage
- Mission definition; set parameters for robots operation
- Transportation of robot to inspection site
- Robot is raised to power line
- Robot travels on power line
  - Obstacle detection and clearing
  - Inspection
  - Status control and possibly some remote control of robot
- Robot is lowered from power line
- Robot is transported to storage
- Gathered data is analyzed and reported
- Maintenance of robot

This algorithm places demands on the robot, covered in turn in the following sections.

4.3.2 Storage

The robot must be stored in a convenient way. This is also important to facilitate maintenance, as maintenance is easier if the robot parts are easily accessible during storage. The way the robot is stored should also make it possible to transport the robot as standard air cargo. These two demands are contradicting; a compact case is not easily accessible. Two separate storage solutions might be developed to facilitate each need.

Long term storage and transportation of the robot to inspection sites might cause harm to the robot. A case for protection, fitting the standard air-cargo dimensions should be used. Placing and removing the robot from this case should be a rapid process.

For maintenance purposes a cradle is more purposeful. The cradle could support the robot in a position where all parts are accessible and maintained. During development the cradle can act as a test bed and allow hardware such as actuators to be easily tested.

4.3.3 Transportation

The transportation of the robot should not put restraints on the construction of the robot in itself. But easy transportation is essential for the system as a whole to function well and it must be accommodated for. The long term storage solution described under storage above should suffice for foreseeable transportation needs.

4.3.4 Mission preparations

When the robot system is to be used, the robot needs to be programmed with information about the current mission. The information is what the robot relies on to perform an inspection, together with generic routines. Mission parameters will include initial and target coordinates, how many towers will be passed, what kind of towers will be passed, other known obstacles on the line, what data to gather, etc.

4.3.5 Attaching and retrieving the robot to/from the conductor

The high voltage of the power line makes it a difficult task to raise the robot to the conductor. A number of approaches might be considered:

- Using some mechanical arm (well insulated) to raise the robot [14]
- Bringing the robot up a tower and lower it to the conductor from the tower
- Lowering the robot to the conductor from a helicopter [11]
- Throwing a rope over the conductor and pulling the robot up

The mechanical arm approach would require a substantial development effort in itself. Climbing a tower with a possibly very large and heavy robot is a dangerous task, even if there was no high voltage power line close by. Lowering the robot from a helicopter is straightforward and proven, but bringing in a helicopter defies one of the purposes of the line inspection robot – to get rid of the flying machines. So from this short list of methods only the rope remains.

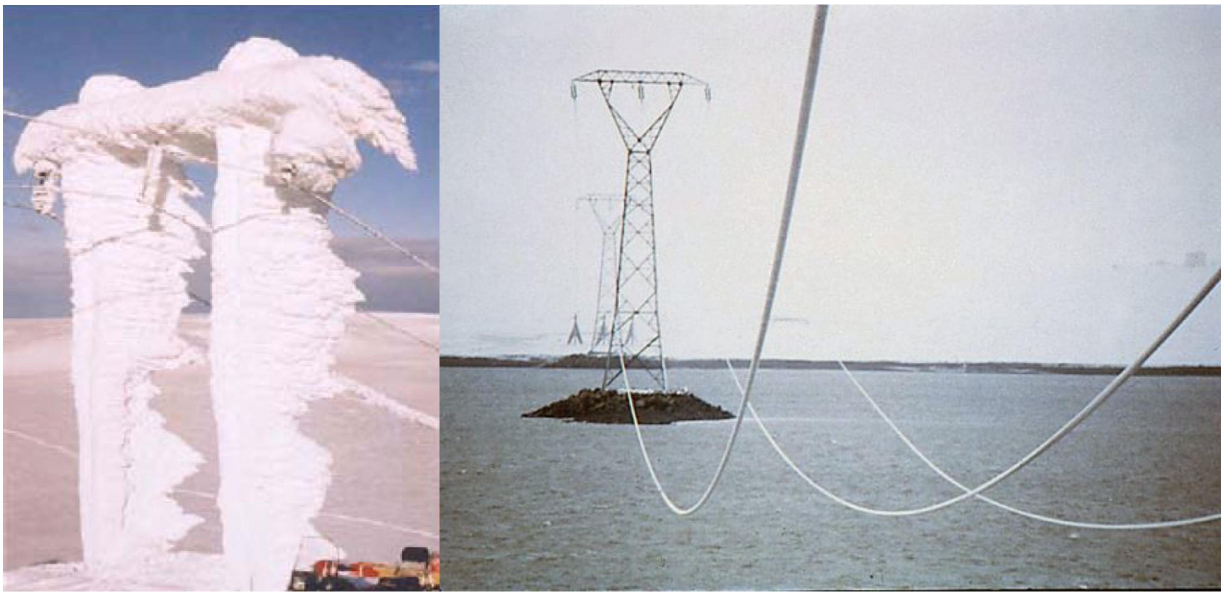

Figure 8 Ice on power lines. To the left is a power line tower in northern Sweden, on the right is a power line in Iceland crossing a lake.

Ice on power lines is a problem, see Figure 8. In Sweden, ice is removed from the conductors by throwing a non-conducting plastic rope over the line. A short stretch of linked chain is attached to the middle of the plastic rope. This chain is pulled up and then back and forth over the conductor, removing the ice. The plastic rope is insulating (if clean) and a method for raising and lowering the robot to a power line might be adopted as follows:

1. Throw a rope around the conductor
2. Attach the robot to the rope, in a way so the robot can release itself
3. Raise the robot
4. The robot attaches itself to the conductor

To bring the robot down:

1. Throw a rope over the conductor
2. Let the robot attach to the rope
3. The robot releases the conductor
4. Lower the robot from the conductor

This method requires the robot to be equipped with some device enabling it to grab and release a rope. It is considered likely that a mechanism gripping an electrical conductor might be adapted to the dual use of also gripping a rope.

Other approaches to raising and lowering the robot are most likely very possible.

4.3.6 Obstacles

The line inspection robot will climb on the live transmission line wire, and it must be able to pass expected obstacles in its way. Power lines come in a multitude of forms and so does the obstacles the robot must face. But just as there are many differences between different power lines, there are also similarities. Some common obstacles are listed below ([15], [2]).

- Insulator
- Bundle conductors with spacers
- Vibration damper(s)
- Tension clamp
- Transposition
- Aircraft warning spheres
- Unknown obstacle

All of these obstacles, except perhaps the unknown, are present on all power lines. If a robot is to operate autonomously for prolonged periods of time it must recognize, and should be able to pass, all of these obstacles. The passing of the obstacles pose different challenges, but two main categories are detailed in Table 1 below.

Category	Passage method	Obstacles in this category
Interrupted line	The robot is faced with an obstacle interrupting the line. It must grab the line on the other side of the obstacle and thus climb past it.	Insulator Bundle conductors with spacers Vibration damper(s) Aircraft warning spheres
Vertical phase-line	The line after a line interruption is nearly vertical. The robot must be able to grab and hold a vertical line, and to move along it.	Tension clamp Transposition

Table 1 Obstacle categories.

Detailed descriptions of the various obstacles are given below.

4.3.6.1 Insulator

An insulator attaches the conductor to a tower or other structure, see Figure 9. The exact configuration of insulator relative to tower is very varied. When climbing around this type of obstacle it is vital not to protrude too much from the live line. Unless the extending part is entirely shielded and does not conduct electricity, it might cause flashover between live line and grounded structure. In the majority of transmission towers it is safe to extend below the line while climbing, but there are unfortunately many cases where this is not true and where it is better to extend to the sides.

Figure 9 Insulator (110 kV duplex).

4.3.6.2 Bundle conductors with spacers

High voltage power lines with single conductors implicitly have extreme electrical fields close to the conductor. The high electric fields focus at protrusions from the conductor and if strong enough form a corona.

Using multiple bundled conductors separated by spacers (Figure 10) is one common way of alleviating corona issues. Bundled conductors dilute the electric field to the point where no coronas form. In the Swedish transmission grid maintained by SvK, some 15000 km of 220 kV and 400 kV power lines, twin or triple bundled conductors is used without exception.

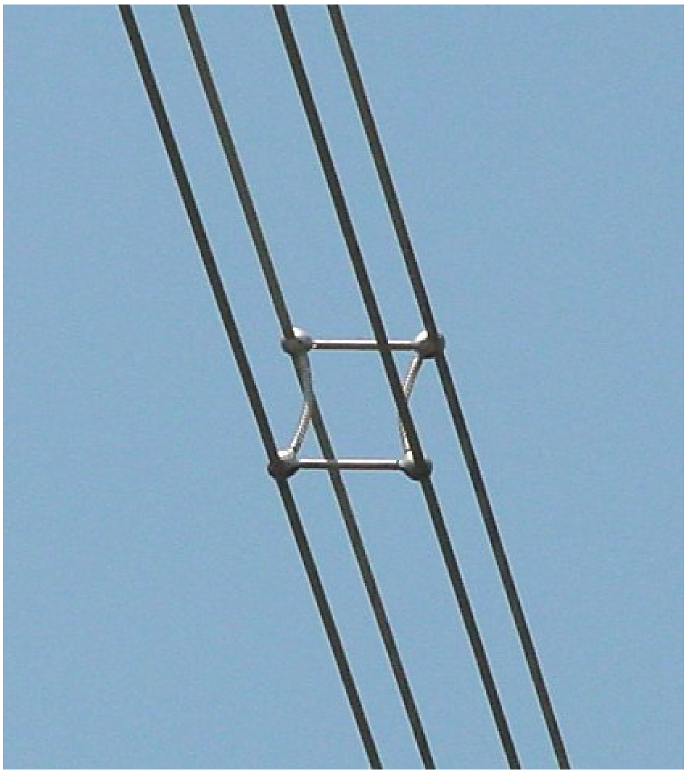

Figure 10 Bundle conductor with spacer.

Spacers on a bundled conductor occur much more frequently than towers and other obstacles on non-bundled conductors, so a robot designed to operate on a bundled conductor must be very good at navigating around these obstacles.

As obstacles, spacers are frequent but not critically difficult as they generally occur in areas where there are no other phases or grounded structures in close vicinity of the obstacle. There are, of course, exceptions to this as to everything, and spacers on bundled lines occurring on the loop in a tension clamp (covered below) might pose quite a challenge to climb around.

4.3.6.3 Vibration dampers

Vibration dampers are placed on conductors to minimize the effects of wind-induced vibrations [16]. The Stockbridge type dampers vary between 0.5 and 0.8 m in length (Figure 11) [15]. The number of dampers varies between 0 and 4 per span of power line between two towers (0-4 per phase line). Dampers are placed 0.8 m or 1.5 m measured from the centre of the suspension clamp to the centre of damper clamp.

Vibration dampers occur sometimes in pairs and relatively close to towers. Thus they add to the difficulty of passing obstacles on the conductor. If obstacles occurred one on one separated by a length of empty wire, a method to climb around obstacles could be used that relied on this empty space. As it is, any method of clearing obstacles must take into account that the target stretch of conductor after an obstacle might be short.

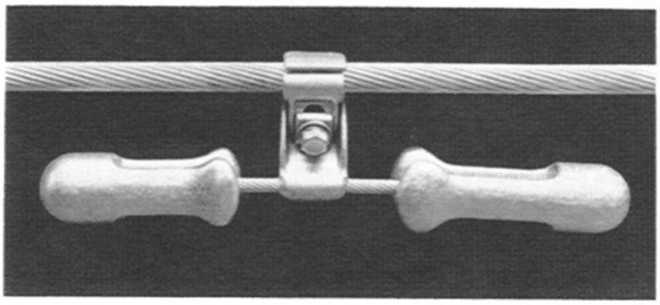

Figure 11 Stockbridge-type vibration damper.

4.3.6.4 Tension clamp

Tension clamps, as can likely be deduced from the name, adds tension to the conductor. In a long stretch of straight power line, about every tenth tower will carry tension clamps. In mountainous areas this ratio might be different. In, for example, parts of Malaysia with rough terrain 50 % of towers carry tension clamps.

A tension clamp consists of two insulators adding tension to the conductor spans extending from the tower. Below the insulators, the conductor extends in a loop below the tower. Sometimes the conductor loop is held down by weights or insulators to keep it out of harms way. See Figure 12.

As an obstacle, a tension clamp is a formidable challenge - and one that must be conquered. The loop of the tension clamp is not under any tension and thus any technique for clearing obstacles relying on wire tension will run into difficulties here. The loop also descends almost vertically from the mouth of the tension clam so the mechanism gripping the conductor must accommodate for this. A further difficulty is the potentially close proximity of grounded structures. Different phases might also pass close to each other in some vertically arranged towers with tension clamps.

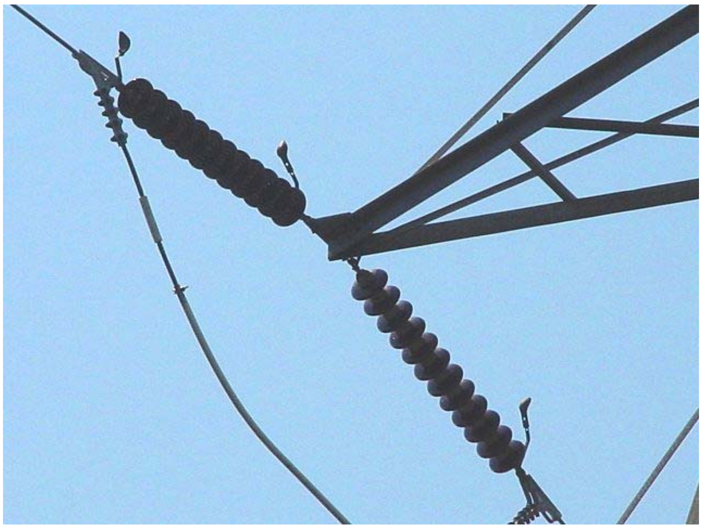

Figure 12 Tension clamp.

4.3.6.5 Transposition

The three phases on a high voltage power line are electrically different. The phases on the side of suffer higher resistances than the phase in the middle. To counter this phenomenon, the lines are rotated in regular intervals (10-30 km [5]) so the phases change place. This occurs regularly on all larger power lines and is called a transposition of the power line.

As can hopefully be seen and understood by looking at the illustrating picture below (Figure 13), a transposition is quite complicated. It is hard to tell where you will be at any moment if following a conductor through a transposition. There is little tension on the conductors of the transposition loop and the relative position of the conductors of the different phases may vary during the climbing of the robot. It is also almost impossible to give any safe estimation of how much a robot can extend from a conductor without potentially causing harm during transpositions. Transpositions are generally constructed with a safety distance between different phases but it is impossible to tell how large this safety distance is.

Figure 13 Transposition.

A robot able to pass all other obstacles, but unable to pass a transposition, might still be useful. Such a robot would need a much higher level of human involvement during inspections than one able to pass transpositions. No calculations are supplied in support of this statement; but the high operating costs of aircraft would likely make such a limited robot an economically favorable inspection method.

4.3.6.6 Unknown obstacle

Besides these obstacles there are numerous obstacles on power lines that just don't fit any of the above categories but still block the path of a robot. Some examples of the strange creatures power lines can be are shown below (Figure 14). A robot needs not be able to clear every conceivable obstacle, the categories above should suffice. A robot needs, however, the ability to distinguish obstacles it does not know from the categories above. If faced with an unknown obstacle, the preferable choice is to document the obstacle and contact some sort of operator station where human operators can decide on what action to take. Perhaps a brief remote operation of the robot is enough to get the robot through the difficulty, or perhaps the robot needs ground assistance to clear the obstacle.

Figure 14 Difficult obstacles; a substation (left) and two tension clamps with creative cable loops.

4.3.7 Inspection

Inspection boils down to what and how: What is going to be inspected? How will the robot inspect that? One can approach this from two directions. If it is decided what the robot is to inspect one can then decide on a method to inspect that. Going the other way, one can look at the available sensors and what can reasonably easy be inspected using known techniques and conclude that that is a reasonable target for the robot to inspect.

4.3.7.1 Needs

There are some standard items that inspectors look for when doing their foot or air surveys of power lines:

- Damaged equipment
- Foreign objects on equipment
- Vegetation within safety distances

More exotic items to inspect can be added to this list, such as line integrity, status of compression splices, corona discharges, sagging, etc. The basic inspection need is covered by the inspection of equipment and vegetation.

The main problem is to assess whether or not equipment is damaged or foreign objects are present. It is hard to distinguish what is a foreign object on a power line which the robot has never seen before.

4.3.7.2 Possibilities

Current automated inspection is dependent on the sensors used. Cameras (IR, UV or normal light) are the most common sensors. Audio recording is also easily obtainable. There are many special types of sensors which might be very useful for a line inspection robot. Examples are magnetometers supplying accurate readings of magnetic fields, or accelerometers which can also act as inclinometers returning the current orientation in space of the robot (i.e. tell which way gravity pulls).

The literature survey covers sensors in more detail, but it is a vast area with so many possibilities that it is difficult to provide a decent reflection of what’s out there.

4.3.8 Communication during inspection

Remote communication with the robot is needed for a number of reasons. The status of the robot can be monitored, if the robot runs into trouble it needs to contact some support function, and should the robot really fail, its last known position is vital in retrieving it.

Communicating with a robot in remote areas can be done in several ways:

Satellite
Cellular phone networks
Radio communication
Transmitting signals on the power line

This short list of methods with which to communicate should not be seen as complete, other ways probably exists. The techniques are all limited; Table 2 attempts to sum up the limitations. Details on the techniques are given in the next section.

Technology	Benefit	Limitation
Satellite	Full cover	Limited bandwidth Expensive (compared to other techniques)
Cellular phone network	Cheap Available off-the -shelf	Limited cover
Radio communication	Full cover during short inspections from mobile base	Limited cover during longer inspections Base stations needs to be supplied to remote locations
Transmitting signals on the power line	Full cover	Communication gear needs to be installed on the phase lines

Table 2 Communication technology comparison.

4.3.8.1 Details of communication techniques

Satellite communication offers total cover. The down-side to using satellites is the cost, which might be prohibitive if large amounts of data need to be transmitted.

Using the cellular phone networks for communication is straight-forward, but only works in areas with cell-phone cover. Those areas might be far between on a remote power line.

Radio communication is a tempting choice if the inspection is to be surveyed from a remotely situated base station. If the scenario is that a truck brings one or more robots out for inspection and then remains in the area while the inspection is performed, then radio communication might be the way to go. If the robots are to be placed on the power line and then left for weeks on end, then RF communication is not so good.

The transmission of signals on the power line, like satellites, offer total cover; the robot will never leave the conductor and will thus always be able to communicate. The problem is the need for fixed communication equipment to relay signals from robot to base station.

The by far simplest and most accessible technique is communication over cell-phone network. Modules that offer such communication can be bought for little money and easily added to small form-factor embedded systems. In the prototype stage it is probably the best solution, as a prototype will not be tested out of range from mobile phone networks. In later development of a line inspection robot into a full product, other means of communication might have to be used.

4.3.9 Data analysis

Inspection will gather lots of data, in the form of video, pictures, audio-data and other sensor readings. The analysis and presentation of this data will determine how useful the inspection is. The final inspection robot system will contain automated tools for data analysis where it is applicable. The exact nature of that analysis depends on the sensors used and the raw data they provide.

4.3.10 Maintenance

The line inspection robot needs to be built with accessibility and ease of inspection in mind. This is perhaps not paramount to the final product, but in the prototype accessibility can be very helpful. Problems are likely to arise during the construction and testing of the prototype, and it should be as easy as possible to determine what the cause is. This applies equally to the mechanical and the software engineering and design.

A well thought through and visible debug panel, some indicating lights or the ability to connect a monitor to the line inspection robot can save a lot of time when an error occurs. If a problem arises it can be determined if the problem is in hardware or software, if a microcontroller has malfunctioned, if the internal or external communication works, if the operating system booted successfully, if the software application controlling the robot is up and running. This is an important topic. If diagnostic methods are built into the system from the start the time designing and building the first prototype will be increased, but the overall design time of the system will be decreased.

Maintenance is also discussed under 4.3.2 above.

5 LITERATURE SURVEY

As part of the pre-study, an extensive literature survey has been conducted. The literature survey presents an overview on the use of robotics in the inspection of overhead power transmission lines. The search method to gather articles is described; it resulted in about 50 articles. These have been analyzed and the content is presented. Three distinct methods of clearing transmission towers and other obstacles are documented. Two of the methods are presented in detail; one robot carries with it a guide-rail on which the robot passes around the obstacle, another robot is agile enough to climb around obstacles using three grippers. Also presented in detail is a robot that gathers power from the live transmission line while operating on it. The content of the other articles is outlined, and many sensors are briefly presented. The impact of the analyzed material on the construction of a novel autonomous robot system for overhead power line inspection is discussed throughout the survey.

5.1 Article selection

A literature survey needs literature to survey. To gather a base of articles on which to base the survey, a search was conducted at the library of Uppsala University. Out of the databases available online [17], the following were believed to contain relevant information.

- ACM Digital Library
- ASCE Civil Engineering Database
- Blackwell Synergy
- Compendex
- Emerald
- Energy Citations Database (ECD)
- ETDEWEB-Energy Technology and Data exchange
- IEEE Xplore
- INSPEC
- Science Citation Index
- Science Direct
- SPIE's InCite Database

Some of these databases might contain the complete information from other databases. Time constraints excluded the option of searching offline databases. Much of the content in the above databases is what is known as grey literature; articles from non-peer reviewed journals, conference proceedings etc. This is something to keep in mind, as the quality of the results may vary.

5.1.1 Systematic approach

Ideally, a literature survey should be done in a systematic manner. A well-defined search method would yield a number of articles as result. The abstracts from these articles would be read, and the resulting articles (after discarding irrelevant material) would form the core of the survey. Such an approach would be reminiscent of the systematic review process. The systematic review was developed for the life sciences, but has recently been adapted to other branches of science such as computer science [18].

An ad hoc initial search on IEEE Xplore yielded five articles ([19], [13], [12], [20], [21]) considered highly relevant. The index terms from these articles are collected in Table 3 below.

Combined Terms (by frequency)	Frequency
mobile robot	5
power transmission line	5
power distribution	3
distributed sensor	2
ground wire	2
industrial robot	2
overhead line	2
overhead wire	2
robot kinematics	2
acoustic sensing	1
autonomous robot	1
collision avoidance	1
computerised monitoring	1
edge detection	1
electric field sensing	1
infrared sensing	1
mobile monitoring	1
obstacle-navigation control	1
optical inspection	1
poles and towers	1
power system measurement	1
power system robotic monitoring	1
robot expert system	1
robot movement mechanism	1
robot navigation	1
robot vision	1
robotic maintenance	1

Table 3 Index terms for relevant articles.

Browsing the table with the index terms, it is obvious that only two index terms are of use to us; mobile robot and power transmission line, and they are only relevant together. All other index terms are either too wide (e.g. ground wire) or too narrow (e.g. power system robotic monitoring) to be of use. Performing a literature search using only one search term is assumed to not yield good results.

It is concluded that a systematic approach based on index terms of articles would not suffice, and that therefore another method has to be used. The initial ad hoc search for articles that yielded the five articles forming the basis for the study of index terms had obviously produced valid results. That search was performed by entering random words thought to be in titles of relevant articles.

5.1.2 Search method

Having thus explored a systematic approach based on index terms, and finding it insufficient, the final search method was decided as following.

1. Search for *mobile robot* and *power transmission line* in the indexing terms
2. Search for the following in document title:
    - *robot* and *power line*
    - *robot* and *transmission line*
3. Search for the following in all fields:
    - *power line* and *inspection* and *robot*
    - *transmission line* and *inspection* and *robot*
4. Try to locate relevant references from read material

5.1.3 Search results

This search approach was first tested on IEEE Xplore, yielding 6 matching articles from the indexing terms, 7 from the titles and 8 from the all fields search. Removing low quality results and duplicates from the different searches, 9 articles remained. This is quite a low number of articles, but keeping in mind the small amount of research in the field it is not a surprisingly small number.

The full search was conducted Monday, October 17, 2005; the results are displayed in Table 4 below.

Article Search Results	Results	
Database	Relevant	Irrelevant
ACM Digital Library	0	4
ASCE Civil Engineering Database	0	0
Blackwell Synergy	0	100+
Compendex	34	100+
Emerald	4	100+
Energy Citations Database (ECD)	1	48
ETDEWEB-Energy Technology and Data exchange	Not available at time of search	
IEEE Xplore	9	1
INSPEC	searched together with Compendex	
Science Citation Index	3	1
Science Direct	1	0
SPIE's InCite Database	0	0
Summary (duplicates removed)	38	100+

Table 4 Results of literature search.

As can be seen from the table, a total of 38 relevant articles were found. The results from Compendex/Inspec suffer from some problems. It was not always possible to locate downloadable copies of them and in some instances the articles were written in Chinese. Abstracts could be located for all 38 results, and based upon the abstracts all were considered relevant. Out of time constraints, results requiring the search of offline databases to be located and foreign language results were ignored in the final thorough reading stage and are not listed among the references of this report.

5.1.3.1 More articles from references

Besides this foundation of about forty articles, resulting from the database search, the list of articles has been improved by locating relevant references and other valuable sources of information. This has for example yielded articles discussing aspects of aerial inspection by helicopter ([8], [10]), and material providing detailed descriptions of power lines [22].

5.2 Three major studies

The articles produced by the literature search have varied content. There is a group of papers describing a Brazilian robot for installing warning spheres on power lines ([21], [23]). There are papers describing image analysis [15], and image blur from moving cameras ([8], [10]). Some papers describe thermo-graphic monitoring of compression splices, methods for detecting flaws in conductors [24], or obstacle avoidance [10].

In this section, three articles have been selected that are considered to be major previous studies in the area of this report. The contents of these three articles will be presented and the implications of the articles on the current project will be discussed.

5.2.1 Japan, 1990; J Sawada et al. [19][26]

This article describes efforts at Tokyo Electric Power Co and Toshiba Corporation to develop a mobile robot that can navigate power transmission lines unattended by human operators. The robot is designed to navigate the overhead ground wire. The most prominent feature of the robot is the 3m foldable guide rail that it uses to negotiate transmission towers, seen in Figure 15.

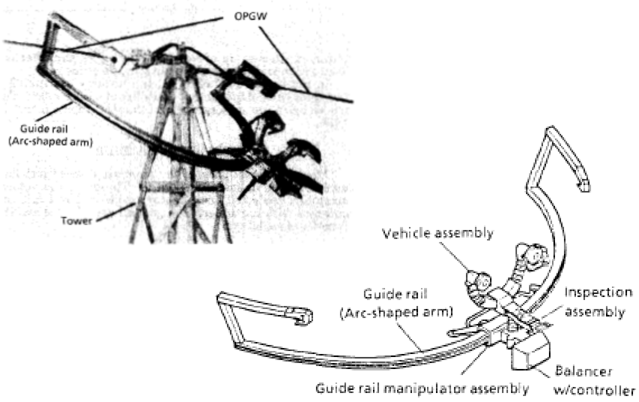

Figure 15 Japanese inspection robot [19].

It is a heavy construction, 100 kg, and the power is derived from a gasoline-powered generator. A prototype was constructed and tested in 1989. Although the guide rail turned out to be heavier than anticipated, the robot still passed the decided requirements. It inspected more than 100 mm wire per second, and it cleared a tower in less than 15 minutes.

Despite attempts at locating such information, it is not known what became of the robot and whether or not it is in current operation.

5.2.1.1 Implications

This construction can be seen as a proof of concept; it is possible to clear a transmission tower by moving on the side of it by some means. One must remember that this robot operated on the overhead ground wire and because of this did not need to take into account electric and magnetic field issues. Since the construction of this robot, great advances have been made in the computational power available from low power, low cost micro controllers. It can be assumed that a present-day construction similar to the one presented in this article would be lighter, cheaper and computationally superior. The solution with a long guide-rail is not suited for operation on an energized phase line, however. It is therefore not possible to use this solution for the line inspection robot to be designed in this pre-study.

The concept of moving on the side of the insulator and other obstacles does not equal the use of a guide rail. A construction with two parts linked together by a rigid axis of some sort should be able to traverse obstacles in this manner, if properly modified. The magnetic and electric field issue must be analyzed before such a solution could be considered for live-wire operation.

5.2.2 China, 2005; F Y Zhou et al. [20][27][28]

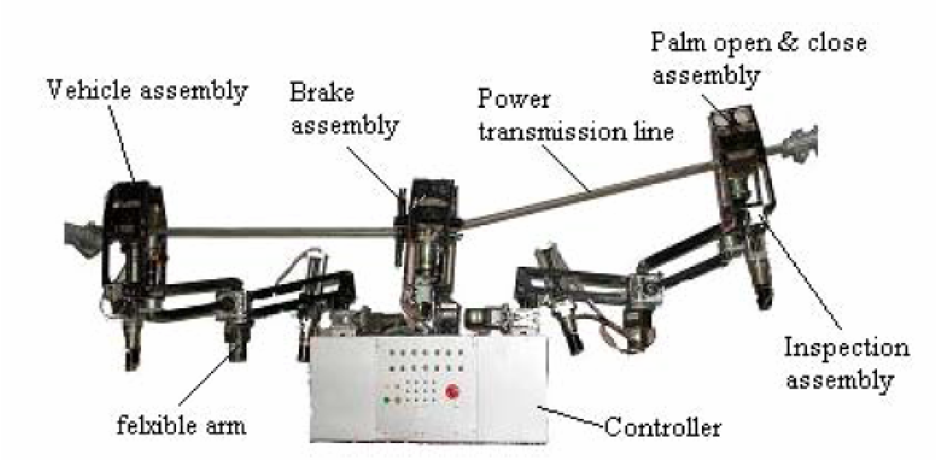

Figure 16 Chinese inspection robot [27].

This robot is very complex; it has a full 16 degrees of freedom (DOF). A Chinese research grant provides the funding for the ongoing project developing this robot system, and many articles have been published about it. The latest article [27] was published 2005, other related articles are [20] and [28], as well as at least five papers written in Chinese.

Most articles related to this development project deal with the control of the robot. With 16 DOF and the power of modern microcontrollers, making this robot do what it is supposed to do is quite a challenging task. The robot has passed tests, clearing towers on transmission lines. Like the 1990 Japanese robot [19] this robot also operates on an overhead ground wire.

The robot is controlled by combination of different languages, C, VC++ and CLIPS. CLIPS is a public domain expert system. Calculations are performed by a combination of on-board processing and processing done at the control station. The control station is housed in a car and communicates by radio with the robot.

It is not mentioned how the robot is supplied with power or for how long time it can operate; the operational range is mentioned as 5 km.

5.2.2.1 Implications

The passed tests show that this construction is able to clear transmission towers. This construction is less protruding from the line it climbs on than the Japanese construction. That is a big benefit if the robot is to operate on a live wire. 16 DOF is a lot though; other papers have mentioned the difficulty of high power consumption even with fewer than 16 DOF. Another problem with a design this complex is the difficulty of controlling it in a safe way. The distributed computing and the mixed languages used for control further add to the complexity of this design.

A robot built along the principles of this robot might work, but the design must be simplified. The degrees of freedom can come down, the programming environment can be made more homogenous, and the computations can be kept onboard. If such a robot is to operate on live transmission wires, the electric and magnetic field issue must be thoroughly analyzed.

5.2.3 Thailand, 2001; S Peungsungwal et al. [12]

This robot is very different from the two previously discussed systems. This is a small construction, built on the concept of gathering power from the magnetic field around the transmission line and using that power to propel a robot along the wire. As shown on the illustration below, the robot is little more than an iron core around the wire with a motor and wheels to propel it and a minimum of other components (including a camera).

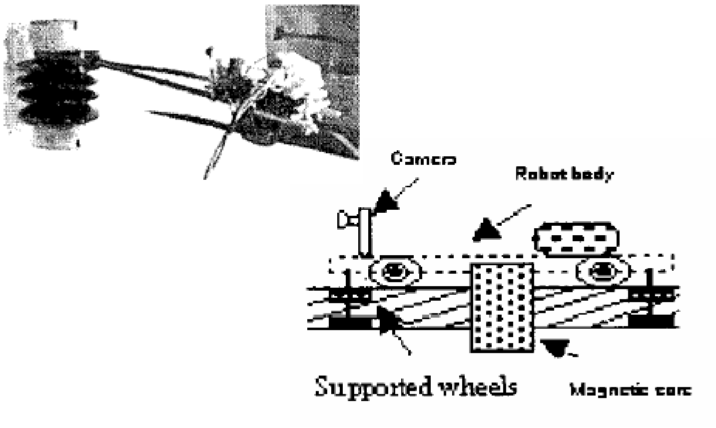

Figure 17 Inductive gathering of power proof-of-concept [12].

The article describes the design, discusses how to gather power from a live wire and then shows that the robot can move along a live wire using the power gathered from it. This robot can for obvious reasons not clear any obstacle except perhaps a compression splice. In its simplicity lies the beauty; this robot is cheap, simple and it does the job it set out to do but nothing else. It shows that at least this small robot is able to operate on a live wire without sustaining damage from the electric and magnetic fields.

5.2.3.1 Implications

Gathering power from the transmission line itself is a clever concept. A robot capable of this, and capable of clearing transmission towers and other obstacles, can take all the time it wants. It can be left at one location and picked up a week later tens of kilometres away. An iron core around the wire, combined with wheels to traverse the wire could be made into a claw. A robot could be designed by many such claws. Some connection between the claws would enable the robot to clear obstacles. A delicate balance would have to be kept between protruding too much and too little from the live transmission wire. Deviate too much from the wire and the magnetic and electric fields cause problems, like corona formation. Deviate too little and the robot is not able to clear obstacles.

5.3 Other articles

The three projects discussed in depth above are just a few of the many variations on the theme of a robot crawling on a wire seen in the articles. As an example; there are two articles discussing a robot design to aid the installation and removing of aircraft warning spheres [21][23]. These articles describe a solution with a remotely operated robot that is elevated up in a transmission tower, equipped with a warning sphere, bringing that sphere out on the live line and finally fixing the warning sphere on the live wire. The sphere mounted by the robot is made up of two halves. The robot is equipped with fittings appropriate for the half-spheres and locking mechanism for attaching the two spheres on the wire, to form a complete aircraft warning sphere.

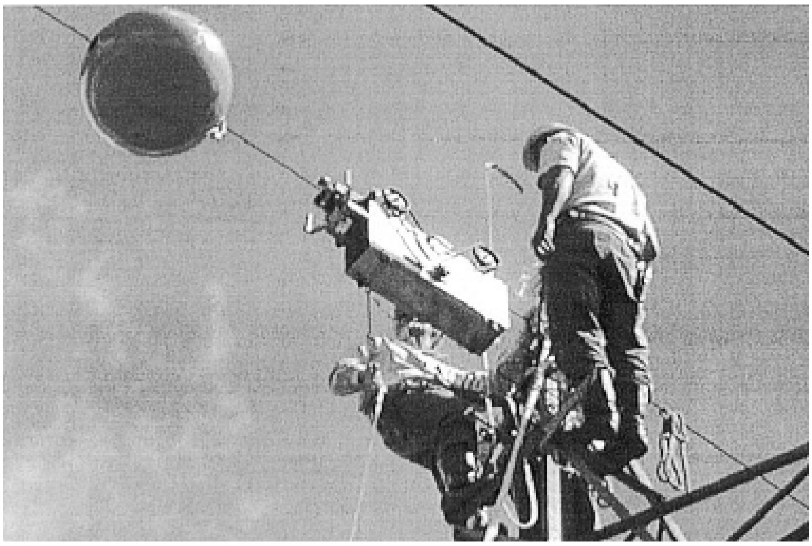

Figure 18 Robot for mounting aircraft warning spheres, in operation on power line [21].

This robot might at a glance not seem to relate much to the problem studied; traversing and inspecting great lengths of transmission lines and multiple towers. However; every robot operating on a power line needs to somehow be placed on that power line. The aircraft warning sphere placement robot needs to be routinely raised and lowered to and from a live transmission line. The method developed to place that robot on a power line might be adopted almost as is to place an inspection robot on a power line. A picture illustrating the placement of the robot on a live power line is shown above.

One paper describes plans for a robot moving on a wire using a snaking motion to clear obstacles [29]. Such a design would protrude very little from the transmission cable and might be very interesting considering the magnetic and electric field issue. There is also a paper exploring the use of a “brachistochrone” movement scheme for a power line surveillance robot [25]. The fascinating gait described mimics that of a cabbage worm. As only simulations are available it does not give a realistic impression.

5.3.1 Sensors

A huge area where much previous work has been done is sensors. Power line inspection is currently routinely performed by helicopter. Much research is focused on improving the quality of the inspection, making it safer and cheaper. Unmanned aerial vehicles (UAV) have been suggested as the next step in power line inspection. Other research has focused on improving the quality of the gathered data by computerizing the inspection process, for example by having cameras that record the flight and automatically target transmission towers [8][9]. Products has been developed which uses a combination of wavelengths including UV to detect coronas during most light conditions [6].

Studies have discussed how to best estimate the remaining service life of ageing insulators [30]. Electromagnetic induction has been used to locate flaws in overhead transmission lines [24]. LiDAR has been used to estimate vegetation that needs removing [31]. LiDAR is a technology similar to radar, but based on a short pulse of emitted light and not radio signals. Mobile sensor systems use GPS to obtain accurate positioning.

The list of methods, used to sense any and everything that can possibly be detected on and around a power transmission line, goes on and on. Many relevant articles are referenced in this document, and many more can be found by using the databases previously listed.

5.3.1.1 Equipped sensors

Although no two robots seem to be equipped with the exact same sensors, some trends are discernible. Most robots and surveillance platforms carry either video or still cameras. Many sensor systems have some way of extracting volumetric information, carrying LiDAR, laser scanners, or extracting distance information from stereo images. Many multipart systems carry GPS modules for accurate positioning. When it comes to sensors for specific use, there is great creativity and a plethora of options. This literature survey is in no way capable of describing all possible sensors used on and around power lines. When the need for a sensor arises the best thing is to look in the databases for specific information regarding that sensor type.

5.4 Results of the literature survey

The literature survey has explored the possibility of autonomously inspecting power transmission lines using a wire-crawling robot. First, suitable online databases were selected. Then, a search method was developed. The search method was first intended to be systematic and based on index terms, inspired by recent development in the life sciences and in computer science [18]. The narrow scope of the studied field and the small amount of published material forced the use of a more pragmatic, but still well defined, search method. The search was performed and it returned about 40 articles. After reading abstracts, and sorting out irrelevant and inaccessible material, about half of the articles remained.

The literature search has revealed previous work covering hopefully all aspects of an autonomous power line inspection robot. Articles describe methods for raising robots to live transmission wires [21], and traversing live wires drawing power from the power line itself [12]. At least three methods have been described to clear transmission towers and other obstacles. A guide rail can be used on which the robot moves on the side of the obstacle [19]. The robot can be made agile with many degrees of freedom and able to climb around obstacles [27]. The third option described is to make the robot perform a snaking motion, crawling around an obstacle [29].

Many articles deal with sensors. Almost all systems include a camera of some sort, sometimes stabilized and with automatic targeting capabilities [9]. Infrared and UV cameras offer extended capabilities for sensing heat and corona on power lines [6]. A plethora of different sensors can be used to monitor different aspects of power transmission lines, for example corrosion detection and different ways of determining insulator status [30]. A full investigation of applicable sensors is beyond the scope of this literature survey.

Hopefully the material presented in this survey can serve as a starting point for designing a novel autonomous power line inspection robot system. The articles referenced herein offer a thorough overview of the area and describes well previously undertaken efforts. If more specific information is needed, the method used to obtain these results has been described and can be used again to locate more information.

6 PATENT SURVEY

This is a survey of the intellectual properties applicable to a potential line inspection robot. The survey is based upon the results of a patent search performed by a patent specialist at ABB Corporate Research.

6.1 Patent search

The patent search was conducted at ABB Corporate Research by a senior patent engineer. The search returned nine patents as being relevant to a line inspection robot, listed below.

- US6523424 B1
- US4268818
- US5565783
- EP0256207
- DE10013392 A1
- US4818900
- US5901651
- US6494141 B2
- AU2001100302 A4

Besides these nine patents, the following two patents where referenced by some of the above patents and where also included on the list of patents to be reviewed:

- US4384289
- US4904996

The total 11 patents are considered to give a good view on the intellectual property situation in line inspection robotics.

6.2 The patents

The patents where located and reviewed using the esp@cenet service. A list of the patents follows, with individual comments.

6.2.1 US6523424 B1

Name: Power line sag monitor

Date: 2005-02-25

Applicants: HAYES RAY M (US); NOURAI ALI (US)

Description: Device for measuring the sag of a power line. This device is attached to the conductor and sends the sag data to a base station. If this information is available to the service operator more current can be transmitted on the line. Without real measurements, the model used is the worst case scenario and the allowed current is smaller.

6.2.2 US4268818

Name: Real-time parameter sensor-transmitter

Date: 1981-05-19

Applicants: DAVIS MURRAY W

Description: Device attached to the power line, measuring its temperature. This information is transmitted either through the ether or by signals on the power line itself. The device gathers electric power from the magnetic field of the power line.

6.2.3 US5565783

Name: Fault sensor device with radio transceiver

Date: 1996-10-15

Applicants: PACIFIC GAS AND ELECTRIC CO (US)

Description: A plastic device attached to the conductor, surveying parameters such as how much current flow through the conductor and what voltage it is operating at. A radio transmitter sends this information to a base-station. Under State of the Art, it is mentioned that it is difficult to fetch enough electricity from the magnetic field of the power line to drive the included components

6.2.4 EP0256207, US4786862 (A1)

Name: Watchdog circuit for transmission line sensor module

Date: 1988-02-24

Applicants: NIAGARA MOHAWK POWER CORP (US)

Description: This watchdog circuit is targeted at a toroidal surveillance module. Electronics is sensitive to interference; this circuit monitors errors and reset an electronic circuit if interference has caused it to malfunction.

6.2.5 DE10013392 A1

Name: Determining variable physical characteristic data for variable position device for carrying goods involves very short transmission only if new data have changed by more than given amount.

Date: 2000-10-12

Applicants: PEIKER ANDREAS (DE)

Description: Supplied description (full patent text is in German and thus inaccessible to the reviewer): *The method involves performing a very short data transmission lasting only for a sub-second period in which the physical characteristic data are transmitted to a remote station. Data are only transmitted if new data have changed wrt. already transmitted data by more than a defined amount, hence detection of the new data and their transmission are performed with minimal energy expenditure. An Independent claim is also included for an arrangement for implementing the method.*

6.2.6 US4818900

Name: Predecode and multiplex in addressing electrically programmable memory

Date: 1989-04-04

Applicants: TEXAS INSTRUMENTS INC (US)

Description: This patent describes a multiplexer for selecting memory cells within a semiconductor.

6.2.7 US5901651

Name: Self-powered trolley for stringing lines between utility poles

Date: 1999-05-11

Applicants: BOYD JIMMY R (US)

Description: This is a simple self-propelled shuttle with the battery as a counter-weight. It is used to string lines between utility poles.

6.2.8 US6494141 B2

Name: Remotely operated vehicle for inspection and intervention of a live line

Date: 2003-08-23

Applicants: HYDRO QUEBEC (US)

Description: This ROV (remotely operated vehicle) is able to travel along a live conductor. The patent describes in detail the grip of the robot around the cable, with wheels, motor and pressure-mechanism for wheels against cable, see Figure 19. The claim is a vehicle with three wheels above the wire for traction and two wheels under the wire for pressure. This construction is in parts similar to the robot developed in this pre-study. The use of two different grippers makes the robot now developed different from the one claimed in this patent.

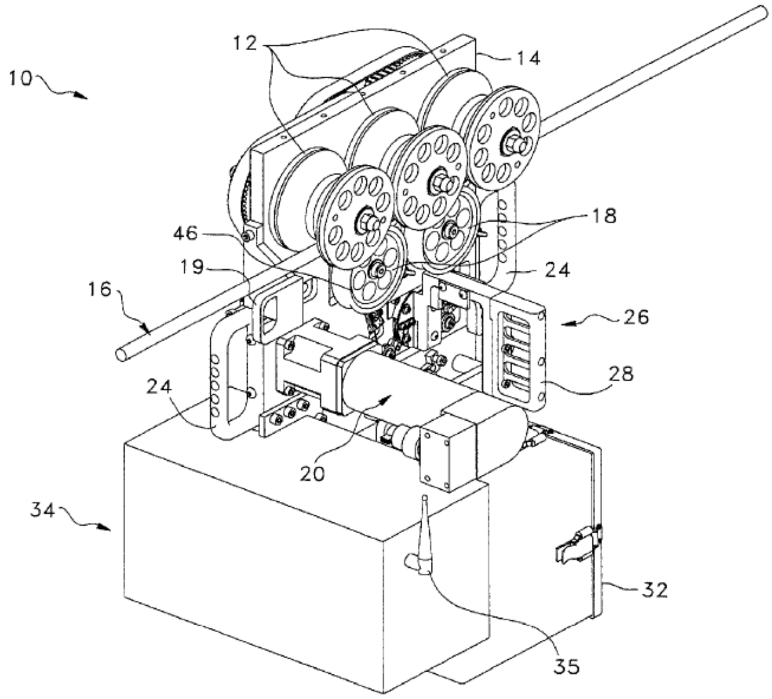

Figure 19 US6494141 B2, ROV for operation on live phase-line [32].

6.2.9 AU2001100302 A4

Name: System and method for electric power transmission line inspection

Date: 2001-09-20

Applicants: TEWES ANDREW

Description: Patent application describing system for power line inspection. The inspection is to be performed by an autonomous blimp.

6.2.10 US4384289

Name: Transponder unit for measuring temperature and current on live transmission lines

Date: 1983-05-17

Applicants: GEN ELECTRIC (FERNANDES ROOSEVELT A)

Description: Toroidal transponder unit mounted on a conductor while monitoring it. Gathers power from the magnetic field of the conductor.

6.2.11 US4904996

Name: Line-mounted, movable, power line monitoring system

Date: 1990-02-27

Applicants: FERNANDES ROOSEVELT A (US)

Description: System for monitoring power lines. This system is designed to move along the conductor, gathering power from it, transmitting data to a base station and passing obstacles on the line. The system is very hypothetical; amongst other things the climbing is to involve helium balloons and propellers making the robot fly over towers. No realistic solution to the climbing problem is presented.

6.3 Results of patent survey

The patent survey reveals an area without much intellectual property activity. Not many patents have been filed regarding line inspection robots. Perhaps this should come as no big surprise considering that the literature survey revealed that not much activity at all seemed to have taken place in the area. The patents that do cover mobile power line inspection are characterized by wild ideas (e.g. autonomous airships) and do not give a realistic or professional impression.

Fixed sensor systems are covered by some patents and development in this area has seen actual products on the market. Patents cover sag monitors and housings for sensors.

7 MARKET SURVEY

This section describes the result of the market survey undertaken as part of the pre-study. The market survey will focus on the Swedish market but will also discuss the South American market.

7.1 Maintenance of the Swedish national electricity grid

The Swedish national electricity grid spans 10600 km of 400 kV and 4400 km of 220 kV power lines. It is the transmission grid from the producing stations to the distribution networks and is run by Svenska Kraftnät (SvK). An overview of the power distribution system can be seen in Figure 20 below.

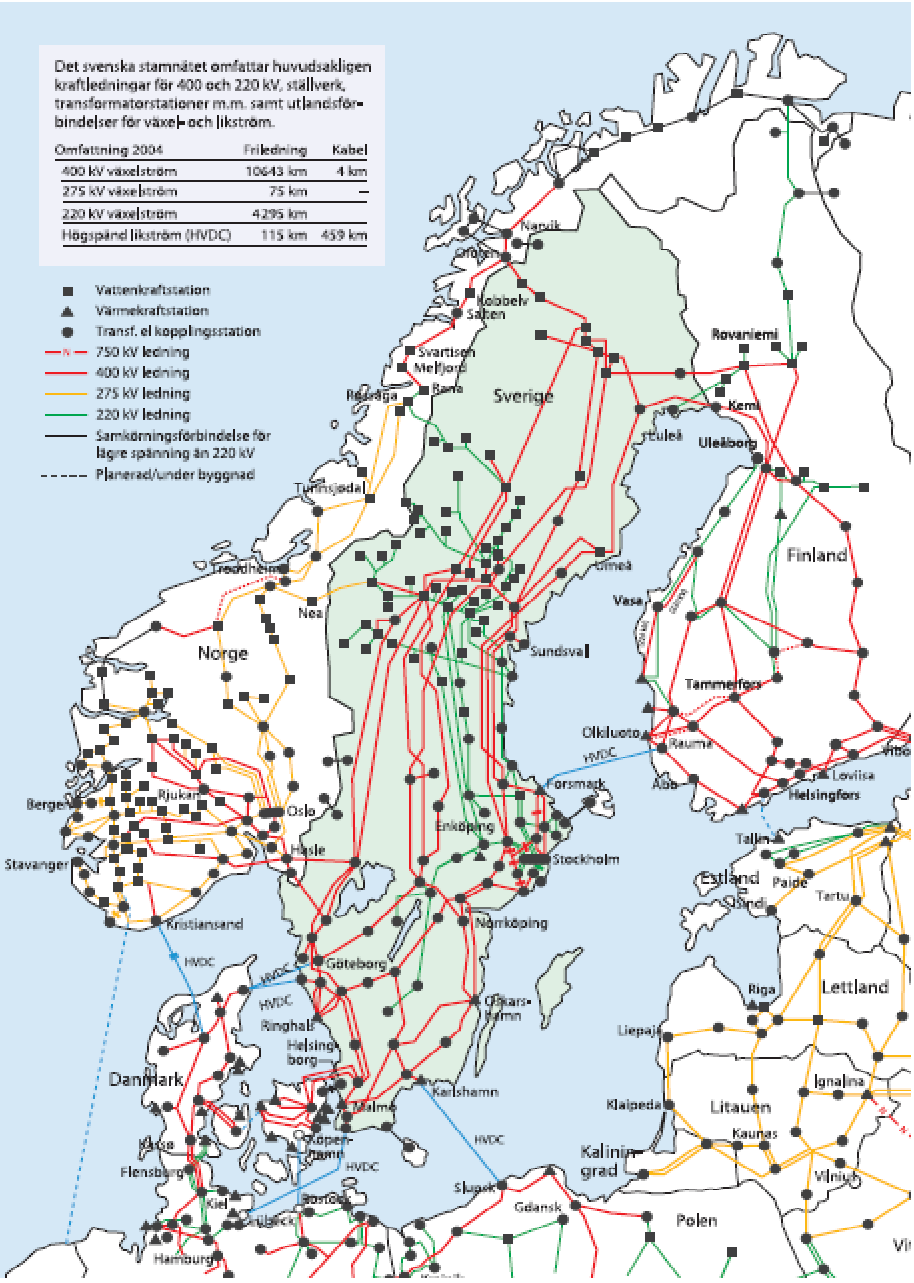

Figure 20 The Swedish national electricity grid [1].

The Swedish power transmission grid is maintained according to the schedule in Table 5 below [2].

Activity	*Interval*	*Method*
Operational inspection of power lines	Every year	Airplane (pilot + spotter)
Operational inspection of vegetation	Every third year	Airplane (pilot + spotter)
Vegetation cutting	Every sixth year	Ground patrol
Maintenance inspection	Every eighth year	Ground patrol
Earth electrode inspection	Every eighth year	Ground patrol
Tower inspection	Every eighth year	Ground patrol
Fault location	On demand	Helicopter or ground patrol
Repair, renewal	On demand	On demand
Other activities (e.g. ice-removal)	On demand	On demand

Table 5 Maintenance schedule for Swedish transmission system.

The most common activity, as can be seen from the table above, is inspection of the power lines. Only if inspection reveals a problem will a ground patrol be sent out to fix it. And even with this maintenance schedule, not all errors can be avoided.

7.1.1 Costs of current inspection methods

Inspection costs for the Swedish power distribution grid managed by Svenska Kraftnät were discussed with a representative from that company [32]. Approximate cost for two types of inspections of 220 kV and 400 kV power lines is compiled in Table 6 below.

Inspection	*220 kV*	*400 kV*
Operational inspection (by airplane)	150 SEK/km	150 SEK/km
Ground inspection *)	1800-2500 SEK/km	1200-2000 SEK/km

Table 6 Inspection costs for Swedish transmission system.
***) Maintenance-, earth electrode- and tower-inspections are usually performed simultaneously.**

If these costs are multiplied by the amount of power line inspected, the yearly cost of inspection can be calculated as approximately 6’000’000 SEK. This figure might seem low, but one must keep in mind that this is only the backbone of the Swedish power transmission grid. The bulk power line length is in the power distribution grid. The distribution network is divided amongst several actors and it is harder to obtain figures for its maintenance.

7.2 The South American market

The South American market is different in many aspects when compared to the Swedish market. The inspection needs are greater due to the more rapid vegetation growth, and the cost of ground inspection is much lower due to lower wages. This means that the outlook for different inspection methods is different in South America than in Europe (with Sweden being an example of the European market). [7]

One implication is that automated techniques will suffer a longer time to market than traditional techniques due to the cheap labor cost. In a country which doesn't yet fully utilize air surveys of power lines, an inspection robot might not be competitive in price.

The line inspection robot will still have the benefit of improved inspection quality. There are features that are hard to inspect from the ground, but which a line-crawling robot can inspect with ease. Contractors might offer the line inspection robot as a service to TSO in South America.

7.2.1 Market size

While the market in South America might not be as big per length of power line as the European market, it somewhat makes up for this in total line length. As an example, The Brazilian transmission network consists of 80'000 km of 130 kV - 750 kV lines, and it is growing. In the years 2000-2004 the system was expanded by 10'000 km, equal to the entire Swedish 400 kV system. [7]

7.3 Product value

Based upon the above calculations of the inspection costs of the grid of SvK, one can approximate the cost of inspection of all 130-400 kV lines in Sweden to 12 MSEK since the total line length of these voltages in Sweden is 30'000 km. If a robot is assumed to inspect lines at a speed of 1 km/h and active 20% of the time, each robot will inspect 2000 km/year. Since inspection quality will be much improved using robot compared to aerial inspection, perhaps TSO will only want to inspect with robot every other year. The last assumption is that a TSO wants payoff on a robot in the first year after purchase.

Putting all the assumptions and facts together, it can be concluded that there is a market for 10 robots in Sweden and that each robot can cost 1 MSEK. Since Sweden constitutes roughly 2% of the worldwide power line market, globally there would be a need for 500 robots.

If a robot has an active service life of 5 years, there would be a global market for 100 robots annually, and earnings of 100 MSEK/year before costs. A very early approximation of cost might be 0.5 MSEK production cost/robot.

8 MECHANICAL DESIGN

In parallel with the work on the surveys, different mechanical designs for a line inspection robot has been explored. The full climbing problem (see section 2; The power line inspection problem) is very complex. The problem of climbing on a power line can be attacked from many angles, and the chosen approach will have a large impact on the future of the project. A good approach enables fast construction of a rough but functional prototype while remaining expandable.

The line inspection robot will contain many systems, electrical, electronic, sensors and mechanics. This section will focus on the mechanical system. The mechanical design will determine what characteristics the robot will have, and define its possibilities of climbing past obstacles. In the literature survey, several robot systems were described which are able to climb on power lines. This section will expand on those designs and propose new ways of climbing.

The process leading up the designs presented here was a brain-storming, with various persons contributing with ideas and comments. Designing a robot able to climb on a power line is an intriguing task. When the author of this report described the project and intended solutions to someone, they would ponder the problem for a while and then go “have you thought about doing …” This section describes the result of all of those meetings and discussions.

8.1 Design A

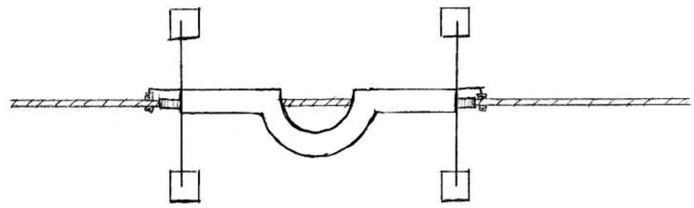

Figure 21 Design A, top view.

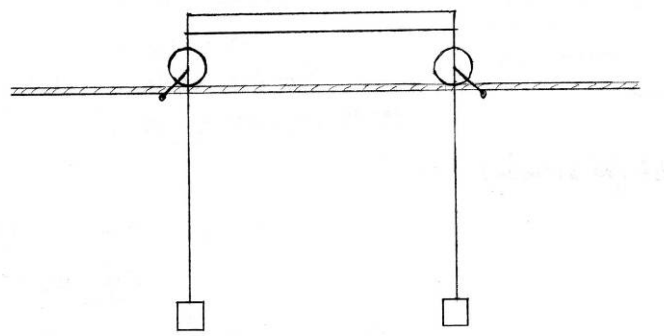

Figure 22 Design A, side view.

Design A originated in previous exploratory work in using robotics for line inspection done at ABB Corporate Research. The construction rests on two sets of wheels on the conductor. The wheel-units are attached to the main robot shell, a beam supporting all robot parts, as seen in Figure 21 and Figure 22. Counterweights (batteries and other heavy equipment) are suspended from the wheels, placing the centre of mass under the robot for static stability.

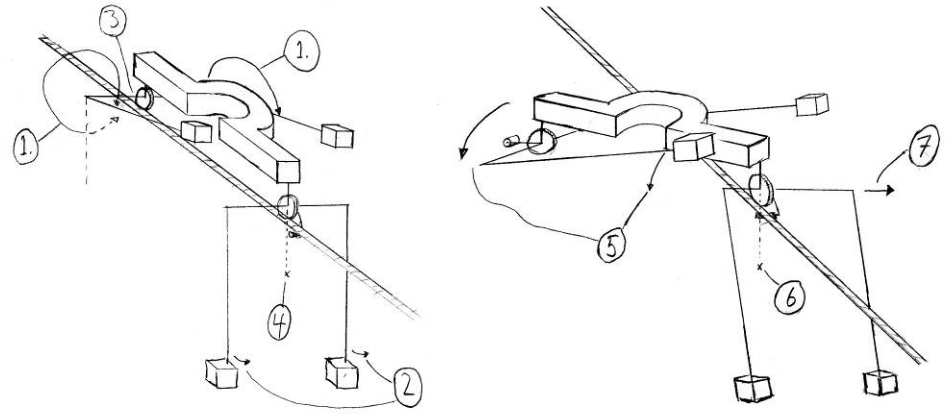

Figure 23 Design A, climbing past obstacle.

When an obstacle is to be passed, the centre of mass is first moved to under the front wheel-unit (Figure 23, step 4). This is achieved by swinging the counter-weights forward (Figure 23, step 1 and 2). When the centre of mass is under the front wheel-unit, the other wheel can detach from the conductor (Figure 23, step 3). The robot is then rotated (Figure 23, step 5) and can clear an obstacle by attaching on the other side of it. During the rotation, the counterweights are adjusted so the centre of mass is constantly under the forward wheel-unit (Figure 23, step 6 and 7).

8.1.1 Advantages

- Easy inspection of insulators as the robot will pass close to insulator during climbing

8.1.2 Drawbacks

Grounded structures on the minimal distance from the conductor are a concern due to the rotating method of clearing obstacles

Stability is a concern, especially in windy conditions, as the robot is only attached by one wheel-unit during rotation

8.2 Design B

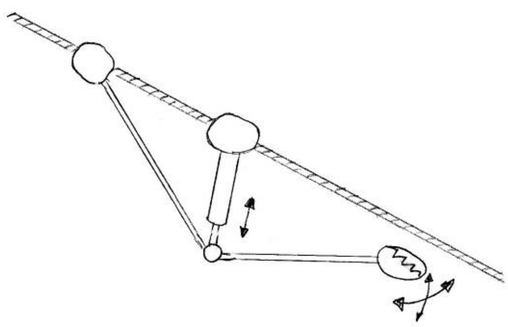

Figure 24 Design B.

A Chinese robot was described in the literature survey (page 27). Design B was inspired by that robot, but attempts to solve some of the problems the Chinese had with their design. Namely, it is the extravagance in degrees of freedom and the complexity in control that is tried to be minimized.

A robot based on this design is very agile and can pass almost any obstacle. The robot has three arms, all of which are movable and able to attach to a conductor from many angles. It climbs on a conductor much like a human or chimpanzee would. A human or chimp with three arms, that is.

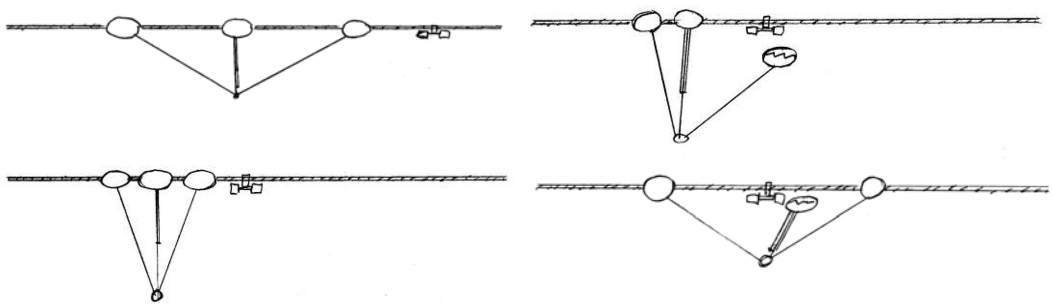

Figure 25: Design B, climbing.

Compared to the Chinese robot with its 16 electrical motors, this design is simpler but still very agile. To perform the climbing illustrated in Figure 25, the robot needs only 4 motors. The robot will also need at least one motor for movement along the conductor and it might need motors for aligning and attaching the wheel-units. The control of this robot should be radically simpler than the Chinese one, as at most two motors will be simultaneously active during even the most advanced climbing operations.

8.2.1 Advantages

- Agile
- Few degrees of freedom

8.2.2 Drawbacks

- Hangs down from the conductor, possibly a problem at transpositions
- Large momentum on parts of the construction during climbing

8.3 Design C

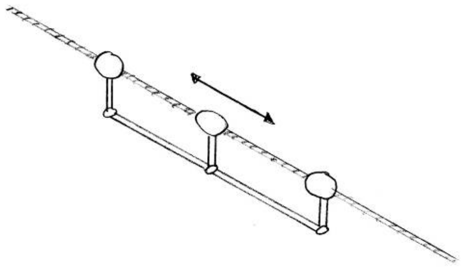

Figure 26 Design C.

This design has one goal; to be as close as possible to the cable at all times. The objective behind this is the fear of flashovers over the robot to grounded structures and the possibilities of corona discharges and other electrical field issues.

A robot based on this design consists of several (at least three) wheeled attachment units (Figure 26). The wheel-units are connected by beams equipped with actuators. The actuators enable an individual wheel-unit to detach from the conductor during obstacle clearing.

Design C is unique in that it is expandable. A base of three segments can be expanded with additional segments. A solution is envisioned where basic navigating sensors and equipment is installed in the base, and more advanced and specialized sensors and monitoring equipment is available through additional segments. In use, only segments needed for a particular inspection would be used.

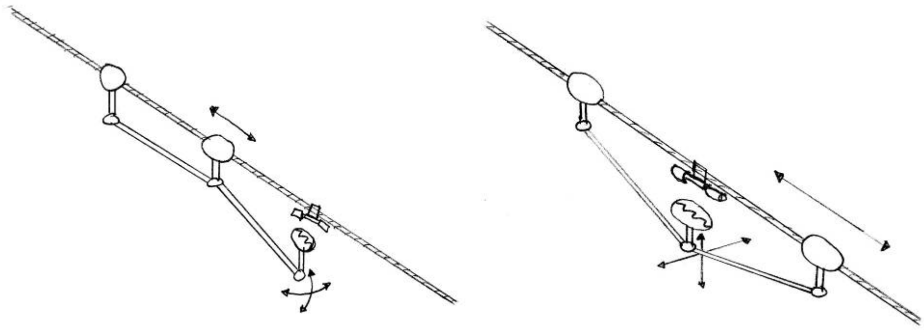

Figure 27 Design C, climbing.

The robot climbs by detaching one wheel-unit at a time while moving forward on the conductor (Figure 27). This robot will be more complex to control that the other designs, but simplicity was not the objective behind this design.

8.3.1 Advantages

- Close to the conductor
- Expandable

8.3.2 Drawbacks

- Multiple obstacles can be a challenge
- Large obstacles can be a challenge
- Complex control of climbing gait

8.4 Other designs

Here are presented additional designs that surfaced during the project.

8.4.1 Brachiating movement

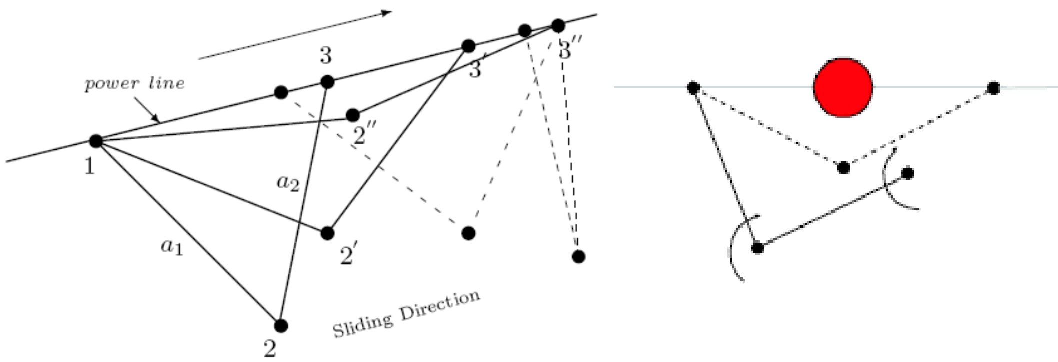

Figure 28 Brachiating movement [25].

A brachiating gait for moving along conductors was described in one of the papers presented in the literature study [25]. The movement is similar to that of a cabbage worm, as illustrated in Figure 28.

8.4.2 Flying

The patent survey unveiled a patent application on a system of autonomous airships for power line surveying (page 33). Various web searches made during the project also uncovered attempts from around the world at flying past obstacles on power lines.

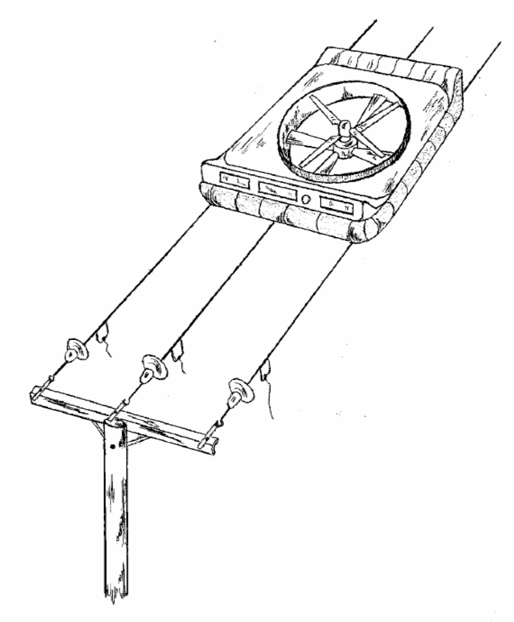

Figure 29 Concept illustration of power line inspection vehicle able to fly past obstacles [34].

Most of the flying solutions focus on using UAV (Unmanned Aerial Vehicles) for power line inspection. Some solutions speculate in constructing vehicles resting on, and gathering power from, the conductor but flying past obstacles. One such concept is illustrated in Figure 29; a robot resting on all three (!) phases of a power line, gathering and storing power used to fly past obstacles [34].

9 REQUIREMENT SPECIFICATION FOR THE PROTOTYPE

The goal of the pre-study is to deliver a well thought out and properly motivated prototype. The prototype will be constructed and filled with sensors and algorithms by a project-course at Uppsala University. The project course will start in immediate succession to the degree project. The task of the degree-project is to produce this report and blueprints for the prototype.

The work to be done during the project course is defined by the requirement specification control document. This document lists all requirements on the system and it is this document the course members will go to, to find out what is done and what is left.

In this section the requirement specification is given in full text, stripped only of headers and version-control and adjusted to the heading enumeration of this document. This is version 1.0 of the requirement specification; at the time of reading this a more recent version might be available.

9.1 General requirements

This section lists requirements that are neither specific hardware nor software requirements, as well as requirements that are both hardware and software directed.

9.1.1 Deployment

At most two operators shall be able to deploy the robot in less than 40 minutes. This time is to be counted from when the robot is packed in the transportation container to when it is properly placed and ready to start inspection on the power line. The time it takes to set mission parameters will not be included in the deployment time.

9.1.2 Operator interface

There shall be a convenient interface available for defining the operation of the robot during the inspection. This interface shall be available when the robot is in storage, at the deployment site and during robot operation. The communication between robot and interface shall be bandwidth-aware.

A human operator shall be able to operate the robot remotely using this interface. The operator interface shall serve as a control and management interface, displaying status and allowing an operator to query and modify parameters. The operator shall be able to override autonomous operation.

9.1.3 Taking down

At most two operators shall be able to take down the robot in less than 40 minutes. This time is to be counted from when the robot is on the power line having finished the inspection to when it is packed in the transportation container.

9.1.4 Movement

After deployment, the robot shall autonomously travel along the power line in a programmed direction. It shall keep traveling along the same line until either of the following conditions is fulfilled:

- The line ends at a substation
- A pre-programmed time is reached
- A pre-programmed distance has been travelled
- The robot reaches pre-programmed destination coordinates
- The robot receives instructions to do something else from an operator
- The robot reaches an obstacle that it classifies as impossible to pass safely

9.1.5 Obstacle passing

The robot shall autonomously pass the following obstacles:

- Insulator(s)
- Vibration damper(s)

The robot may autonomously pass the following obstacles:

- Tension clamp
- Spacer of twin or triple bundle conductors
- Transposition

When the robot encounters an obstacle that it cannot classify into one of the above categories, it shall not attempt to pass it but rather halt and alert an operator.

9.1.6 Inspection

The robot shall perform inspection of the following features:

- Insulator
- Conductor
- Vegetation
- Towers

9.1.7 Communication

The robot shall communicate with its operator using a wireless interface. The interface shall use GPRS, 3G, NMT, satellite data link or an equivalent technology.

9.1.8 Safety

The robots shall be designed such that the risk of injury on human operators, other humans, the power line system or the environment is minimal. The robot shall comply with the following safety regulations:

- SS-EN 50341
- Applicable and up-to-date regulations from the Swedish National Electrical Safety Board (Elsäkerhetsverket)

9.1.9 Technical report

A technical report shall be created and continually updated throughout the project. The report shall follow the ABB technical report template.

9.2 Hardware requirements

Hardware requirements also include requirements on software in local microprocessors in sensors and other subsystems.

9.2.1 General

The robot system, including its cabling and internal and external design, shall make a neat and professional impression.

The robot size shall be restricted to 2 m, measured in any direction.

The robot shall not be heavier than 60 kg.

9.2.2 Electrical and mechanical

9.2.2.1 EMC

Hardware used in the robot shall be designed for electromagnetic compatibility (EMC), to ensure proper operation at the extreme conditions close to live power lines. Tests shall be performed to confirm EMC conclusions.

9.2.2.2 Safety

Any mechanical or electrical system or feature on the robot shall be designed with the safety of people and equipment in mind.

9.2.2.3 Climate

The robot shall be able to withstand a smaller amount of rain and wind during normal operation. The robot shall withstand temperatures from -40 - +60 degrees Celsius.

9.2.2.4 Mechanical shock

The robot shall be able to withstand a reasonable amount of mechanical shock during operation.

The robot shall be able to withstand a substantial amount of mechanical shock during storage in long term storage container.

9.2.2.5 Accessibility

All components, including the batteries, shall be quickly and easily accessible for measurements, repair and replacement.

9.2.2.6 Power supply

The robot shall be equipped with batteries, providing enough power for at least 30 minutes of robot operation.

A device able to capture power from the live conductor by induction shall be developed. The device shall deliver enough power for the robot to be able to charge its batteries. The robot might be equipped with this device.

The robot shall have a connector for an external power source, through which it can be powered during development, testing and maintenance.

The power supply shall be designed in such a way that:

- No electric damage can be done to robot components during operation, storage or charging
- Physical damage from rough insertion or extraction of batteries is eliminated
- No harm, and no interruption of power, will be caused no matter what combination of battery power, external power or power from induction loop is connected or disconnected, as long as sufficient power is available for operation.

9.2.3 Navigation and movement

Any movement the robot makes shall be made in a way that ensures it runs no risk of ever falling from the conductor.

9.2.3.1 Speed

The robots shall be able to move along a power line at a speed of at least 0.5 m/s. It shall pass a standard insulator in less than 10 min.

9.2.3.2 Obstacle passing and hazard avoidance

The robot shall pass obstacles as specified in 9.1.5. The passage of obstacles shall not put the robot within dangerous proximity of other phases or grounded structures.

9.2.4 Sensors

The robot shall be equipped with sensors enabling it to perform any required inspection task. The sensors shall also inform the robot of its surroundings when the robot is moving.

9.2.4.1 Camera / Video camera

The robot shall be equipped with at least one camera or video camera. This camera(s) shall supply moving or still images of at least:

- Conductors
- Towers
- Insulators
- Vegetation
- Obstacles

9.2.4.2 Audio

A microphone shall be present on the robot. This is a TSO (Transmission Service Operator) demand; broken high voltage equipment often emits characteristic sounds.

9.2.4.3 Positioning

The robot shall have encoders on any motors, returning current position and speed of moving parts. The robot shall be equipped with a GPS system to accurately determine position.

9.2.4.4 Environmental sensors

The robot shall be equipped with a thermometer.

The robot might be equipped with a wind meter.

The robot might be equipped with one or more accelerometers.

The robot might be equipped with a smoke detector.

9.2.4.5 Magnetometers

The robot shall be equipped with magnetometers measuring magnetic field along three independent axes. Magnetometers shall be positioned in any parts moving relative the conductor and able to grip it. Analyses of magnetometer data shall be performed and position relative conductor of moving parts shall be calculated from this data.

9.2.4.6 Obstacle ranging and classification

The robot might be equipped with a laser range finder for ranging and classification purposes.

9.2.5 Actuators and indicators

9.2.5.1 Climbing arms

The robot shall be equipped with mechanical arms or other devices enabling it to pass obstacles. These mechanical arms shall be equipped with actuators.

9.2.5.2 Night-time operation

For operation in dark environments, the robot shall be equipped with lights or other solution making the environment visible to the sensors.

9.2.5.3 Status indicators

The robot shall be equipped with status indicators, or a debug panel. This might be realized as a set of LED lights, an LCD display (e.g. AVR Butterfly) or a functionally equal device. The status indicators must be clearly visible from outside the robot. By looking at the status indicators or debug panel, at least the following information shall be available:

- Battery status; at least battery low and battery charging
- External power connected
- Computer status
- State of any controlling software application
- External communication; operation and transmission
- Internal communication (CAN); operation and transmission

Some of these indicators may be located away from the main status indicators / debug panel. The status of any microcontrollers may also be shown, either on the main status indicator or by external indicators on other parts of the robot.

9.2.6 Operator interface

The input device for controlling the robot shall be suitable for controlling the types of movements that the robot makes.

9.2.7 Connections

One shall be able to connect to the robot over the following interfaces:

- An easily accessible terminal interface, such as a serial port or an ethernet port
- Wireless communication over the chosen external interface.

9.3 Software requirements

9.3.1 General

Processing and communication shall be analyzed for real-time requirements, and designed to comply with these requirements.

Any software developed within the project shall be:

- Designed and realized in a well thought through way, following a model for software engineering
- Contain features enabling easy debugging and testing
- Written in one programming language, and one only

- Coded with a defined style (one style only), contain useful commenting, use proper names for variables and contain an up-to-date documentation
- Fault-tolerant; any unexpected event shall result in a determined behaviour (not crash the system)

The software to be developed in this project is described below as being separate applications, but this is no requirement. If properly motivated, all software can be developed as one application.

9.3.2 Drivers

A driver layer shall be developed and used in the software design. This layer shall directly interface the sensors in hardware and provide indirect access to higher layers such as software for control and data acquisition. The use of this layer shall enable the operation of identical control software whether using a simulator or using the final robot.

9.3.3 Control software

Control software shall be created for the robot. The control software shall comply with all requirements related to it as specified elsewhere in this document, i.e.:

- Guiding the robot along the mission, controlling the mission parameters
- Moving the robot
- Making the robot climb past obstacles

9.3.4 Data Acquisition

Software controlling the data acquisition of the robot shall be created. This software shall:

- Align sensors for proper measurement
- Perform measurements
- Analyzing data
- Store results

9.3.5 Communication

Software shall be developed for the communication needs between robot and operator control station.

9.3.6 Simulators

A 3D mechanics simulator shall be developed for training, testing and assertion of the control and data acquisition software.

9.3.6.1 Mechanics simulator

The mechanics simulator shall model the mechanics of the robot with a degree of accuracy that makes it possible to start development of advanced movement primitives by machine learning before the hardware is available. It is recommended that this mechanics simulator is based upon an available standard (e.g. physx from Ageia), or an available open source platform (e.g. ODE).

9.3.6.2 Graphics

The simulation shall be shown in 3D. It shall contain a user friendly GUI. It shall make a professional appearance.

9.3.6.3 Sensors

The signals from the sensors shall be analyzed and simulated to a degree of accuracy that makes it possible to start development of the data acquisition software before the hardware is available.

9.3.7 Interfaces / APIs

Any and all interfaces between different parts of software developed in this project shall be:

- Properly documented
- Designed with expandability in mind

9.3.8 Operator interface

The operator shall:

- Be able to easily switch between autonomous mode and operator mode.
- Visualize robot data and provide controls, allowing efficient operation by trained humans.
- Be platform independent; i.e., it shall work on any common combination of computer and operating system.
- Provide debug features, such as querying and modifying the status of subsystems.

10 PROTOTYPE SELECTION AND DESIGN

Three main designs for a prototype were presented in section 8 (Mechanical design). The designs differ in many important aspects, such as how they pass obstacles and how much they extend from the conductor. This section outlines the thoughts and reasoning behind the choice of prototype and the design of the prototype.

10.1 Trade-off

A trade-off has to be made between the probability of success in constructing the prototype and the probability of the produced prototype being useful. Another important factor to weigh in is the potential for future development of the prototype.

A prototype can be chosen that is simple to construct, with few motors, few moving parts and an easily understood gait. Such a design would likely have a high probability of success in constructing the prototype. The usefulness of the completed prototype would suffer; it might not be able to pass obstacles, placement on the conductor could be a problem, etc.

On the other end of the spectrum is a design with great agility and flexibility, many motors, many moving parts and great complexity in control. The choice of this design would have consequences to the team building the prototype, and the probability of success would be slim. If completed, however, that robot might be revolutionizing.

The chosen way out of the catch, is to go for a simplified version of an advanced design. A simplified design can be easily constructed, and the prototype will accordingly be limited in function. But as it is just the first prototype, and more will follow, it is acceptable if the prototypes to follow can be expected to be better.

10.2 Analysis of the designs

It is now time to look at the suggested mechanical designs from section 8 again. The designs are considered equally capable of solving the complete inspection problem. In this section the designs will be analyzed for three things.

- Complexity
- Simplifications
- Ease of construction of design (possibly simplified)

10.2.1 Design A

Design A is quite complex, with many moving parts. Luckily, simplifications are possible. It is possible to place the main beam under the conductor, rather than over it. Some sort of counterweight is needed to ensure centre of mass is moved from one wheel-unit to the other. This could be accomplished by placing a shuttle on the beam and extending it beyond the wheel-unit mounts.

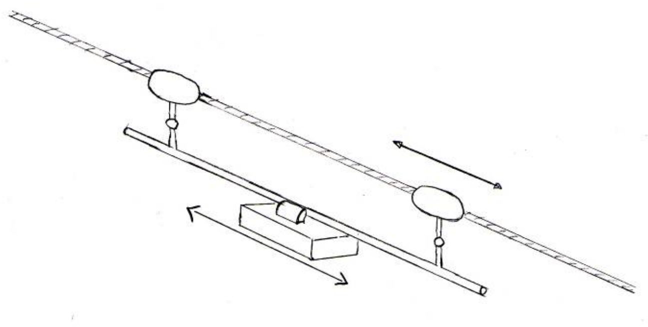

Figure 30 Simplification of design A.

Figure 30 shows what a simplification of design A might look like. During climbing, a robot based on this simplified design has two options, one more than the initial design. One method is appropriate when several obstacles are to be passed on a row. The other method is better when grounded structures are present, but can only be used for solitary obstacles.

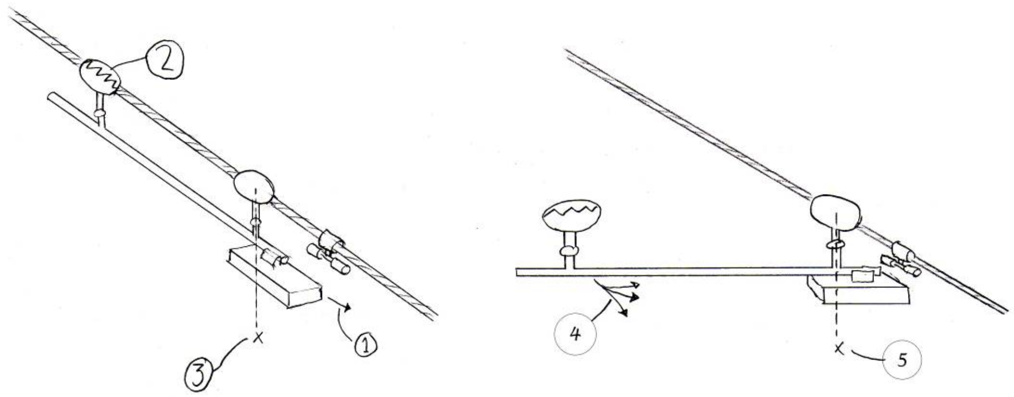

Figure 31 Simplified design A, climbing.

The first climbing method is the main gait of design A. The counterweight is moved forward, placing the centre of mass under the wheel-unit close to the obstacle (Figure 31, step 1 and 3). When the other wheel-unit detaches the robot will be statically stable and able to swing around using very little force (Figure 31, step 2 and 4). After rotation the robot is able to attach to the conductor in a wide arc of possible positions (Figure 32, step 2).

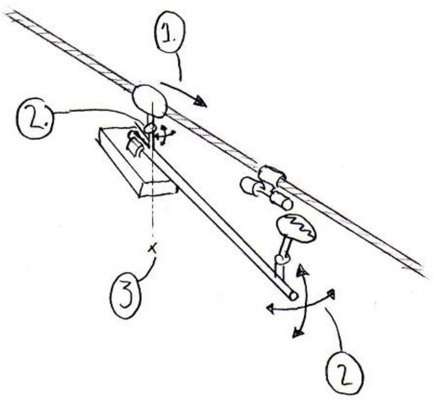

Figure 32 Simplified design A, alternate climbing.

The new design can also pass an obstacle without rotation. In this gait the counterweight is moved back and the front wheel-unit is detached (Figure 32). The robot moves forward attached only with one wheel-unit until the other wheel has passed the obstacle. The design needs only hang down from the line enough to pass the obstacle.

The construction of a prototype according to this new simplified design A is probably possible.

10.2.2 Design B

Design B is hard to simplify, and it is quite complex. The complexity stems from the joint in the bottom of the construction where the three arms of the robot meet and four motors and lots of mechanics needs to be placed. A simple toy-like model (made from LEGO) of the intended design was successfully constructed, without motors.

Simplifying this design is difficult. The design itself is a simplification of a Chinese design, and has already been simplified as far as thought possible.

The construction of a full scale, functioning prototype based on this design might be a stretch for a university project. The focus of the project is intended to be on developing the whole system, not just an advanced mechanical platform.

10.2.3 Design C

Design C is the most complex of all the solutions. There are a lot of motors and moving parts needed for the operation of the three-linked structure on a winding conductor.

The simplification of the design is, like design B, difficult. In this case, it is not an already simplified design that is the problem, but rather the objective behind the design leading to an inherently complex solution. There are simply very few possibilities simplifying a design which main objective is to stay very close to the conductor.

10.2.4 Design choice

It might be obvious, given the space allotted above to the designs, that the prototype will be built according to the simplification of design A. The reasons are given above, but can be summarized as:

- Easy mechanical design
- Good climbing abilities
- Reasonable expandability

10.3 Prototype details

The prototype is designed in CAD using the SolidWorks software. The first step in the design is to fill out the details of the intended design. There are many things left in the description given in the previous sections on design A. Things left undecided are the wheel-units, the joint between the wheel units and the main beam, among other things. In this section these items will be specified one by one, leading up to the final design.

10.3.1 Wheel-units

A wheel-unit is the attachment of the robot to the conductor. The wheel-unit must do the following things.

- Attach (and release) the robot
- Move the robot
- Offer stability against rotation, around the horizontal axis perpendicular to the conductor

Attaching and detaching the robot can be done in many ways. There can be a clamp or lock, closing around a wheel to prevent the robot to fall off. Another possible method is to use two opposing wheels, opening and closing around the conductor. The easiest method is simply using double-flanged or grooved wheels, resting on the conductor without additional support. The risk of using such an approach is that there is no guarantee the robot will not fall off due to wind-gusts or other factors.

The movement of the robot necessitates a motor powering at least one wheel in contact with the conductor. Preferably, all wheels in contact with the conductor are powered. Stability in the required direction results in at least two points of contact.

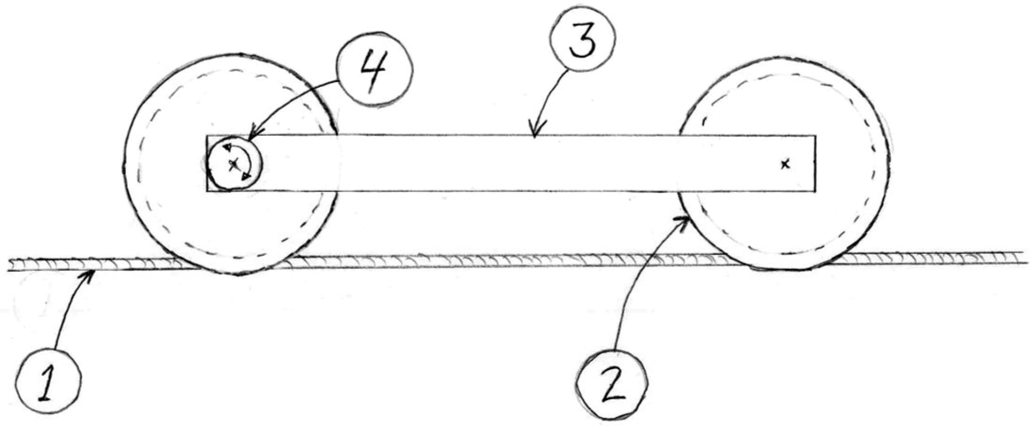

Figure 33 Wheel-unit.

Summing up all requirements and choosing the simplest solution, we are left with two grooved wheels, at least one of which is powered. Attachment and detachment will be done by lifting the wheels on and off the conductor. Figure 33 is a simple sketch of the intended design of the wheel-unit of the prototype. Movement is provided by the motor (Figure 33 label 4) and stability by the two wheels. The diameter and distance between the wheels will be decided when the dimensions of the whole robot are planned.

10.3.1.1 Traction

The traction between the wheels and the phase line needs to be good enough so the wheels don't slip. Discussions with a senior mechanic, Ulf Björkegren, at Svenska Kraftnät [35] resulted in additional focus on traction. Ulf worked with and built cars for transporting personnel on power lines. These cars were used for the last phases in putting up new lines. During the construction of the cars, the traction between wheels and phase line was a big issue, with not even wheels coated with special rubber giving enough traction when wet.

The solution to the traction problem is to use one or more opposing wheels increasing the pressure of wheels against cable. As the here designed prototype is only an early, alpha-stage prototype such a pressure mechanism will not be used. During the development of future prototypes, the pressure mechanism will be an important part of the wheel-unit designs.

10.3.2 Joint between wheel-unit and beam

The joints between the wheel-units and the beam will need actuated rotation along two axes. The rotation will move the beam so the robot can pass an obstacle and attach itself on the other side of it. Figure 34 shows the joint. The arrows from (1) points to the two motors providing movement along the axes of the joint.

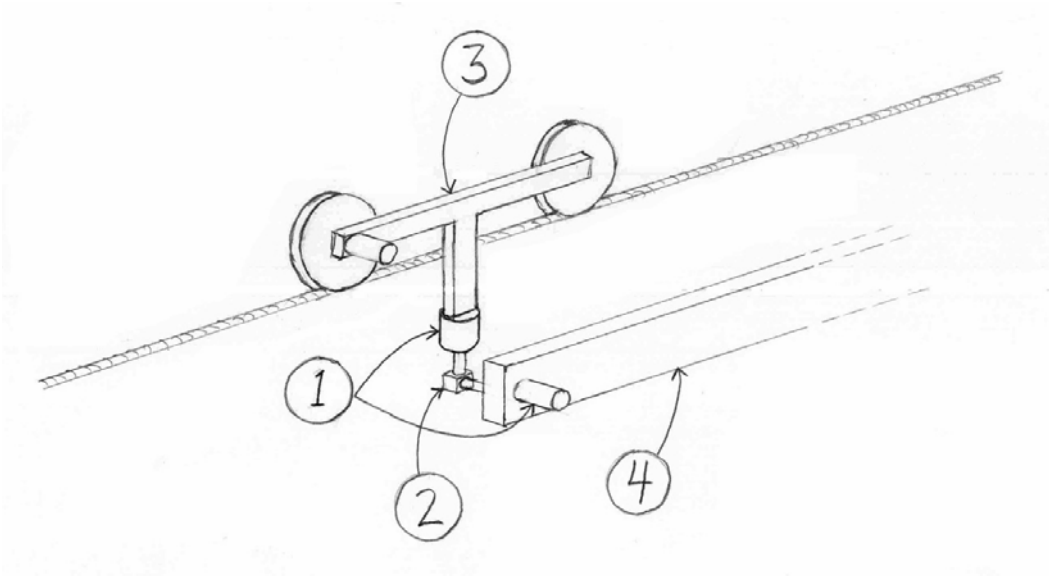

Figure 34 Joint: wheel-unit – beam.

It is not obvious that the solution presented in Figure 34 is the best. A strong electrical motor is either heavy or equipped with a high ratio gearbox. If the motor is equipped with a gearbox, there is a risk of damaging it if a momentum is applied to the output shaft. A solution like the one depicted is heavily reliant on the choice of motors and the momentum provided by them.

If the centre of mass is placed close to the axis of rotation, the need for a strong motor is decreased. There still remains the need for a motor which will not break if a momentum is applied to the output shaft from the gearbox (motor active or not).

10.3.3 Counterweight movement

The moving counterweight proved difficult to design while satisfying all demands. The counterweight is to move between the ends of the beam. In the counterweight, the batteries and most electronics are to be placed. The cables running from the counterweight to the external sensors and other equipment is another challenge to be overcome. If all cables are to be properly shielded from electromagnetic interference they need to be placed inside the robot hull.

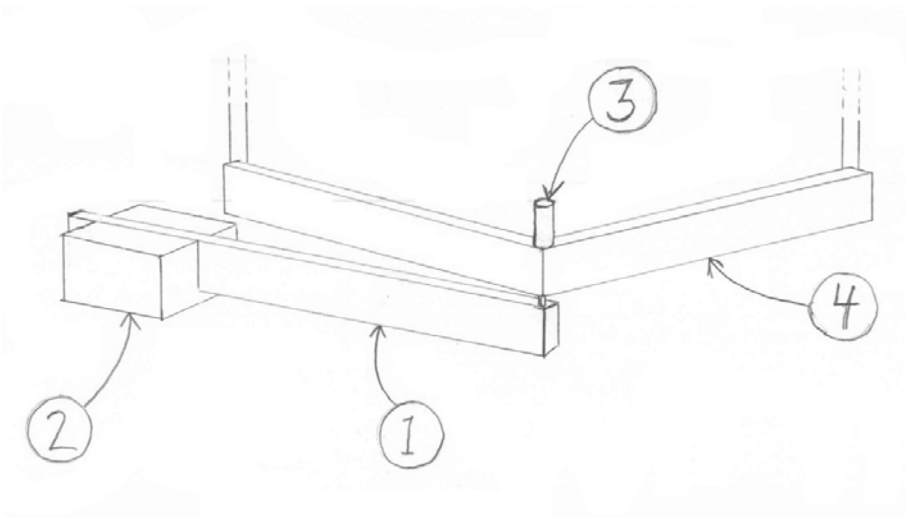

Figure 35 Counterweight solution.

The original plan for the counterweight was to place it on a rail, allowing movement between the end-points. A rail doesn't offer good solution for the cable issue, as it is not determined at construction time how many cables are needed. A flexible flat cable might be used (similar to the cables used in ink-jet printers), but only once it is decided how many cables are needed as such cables are difficult to rewire.

The counterweight movement solution finally decided upon is shown in Figure 35. Instead of placing the weight on a rail, it is placed on a swinging arm (1) attached to the beam (4). A motor controls the arm movement (3). The counterweight (2) is movable on the arm in order to adjust the balance of the robot, but this is only possible during maintenance and not when the robot is actively climbing.

10.4 Prototype design

The prototype is designed using the SolidWorks CAD software. The entire computer design phase will not be described; all important design decisions have been covered already. Figure 36 shows two robot parts designed in SolidWorks.

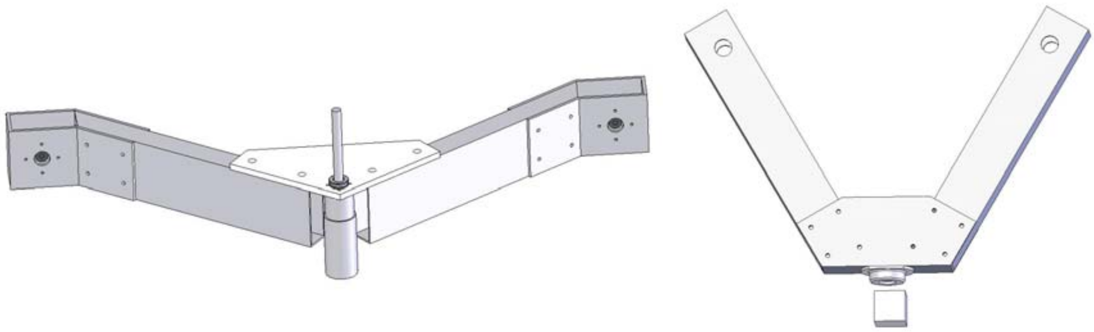

Figure 36 Prototype CAD model.

The very last thing done in the degree project was to hand the design of the prototype over to a workshop for construction.

11 FUTURE OF PROJECT

This degree project is the first stage in the development of the line inspection robot. The degree project was planned to be finished with the design for the first prototype. The design described above thus completes the practical phase.

After the degree project, the prototype is passed on to a project course at Uppsala University. A group of senior university staff together with 12 last-year MSc engineering students will work on the prototype and bring it from design to a working prototype.

11.1 Planned tests

Common engineering wisdom offers the advice: *if you haven't tested it, it doesn't work*. As the university group, to which the project is passed on, hopefully have every intention of making the prototype work, they must test it. Here is given a list of things the first prototype should be capable of doing. This list focuses on the primary task and reason for building the prototype; climbing past obstacles. There is a multitude of other tasks the robot might accomplish, but if it doesn't climb, it is useless.

- Move on the phase line of a power line
- Recognize obstacles on the line
- Pass obstacles recognized as passable
- Transmit data between robot and a ground control station
- Record images and other data of power line equipment

Specific test design is left to the robotics group at Uppsala University.

12 CONCLUSION

This pre-study report has described the power line inspection problem. The report has also presented and analyzed a novel solution to it: the line inspection robot.

If the line inspection robot is to work, it needs to master five key technologies:

- Climb on Energized Line
- Pass Obstacles
- Inspect Equipment
- Autonomous operation
- Gather power from line

These five technologies are all vital to the completed line inspection robot. The technologies were analyzed for relevance in a first, simplified prototype. The decision was made to focus on the second item; passing obstacles. The reasoning behind this decision is that climbing past obstacles is the most difficult to achieve and at the same time the only really novel technology. Passing obstacles is the sine qua non of the line inspection robot.

The report presented previous solutions to the problem, and then went on to describe the solution developed for the new line inspection robot. Focus was placed on mechanical design and many details were given on individual design choices and their motivation.

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