ABSTRACT
Many of the unique abilities that robots possess come from the fact that they are often made mobile. Achieving the mobility required is however rarely done without difficulty. The terrain over which robots must be able to move is often uneven, slippery or muddy, which gives rise to many challenges, particularly stability. Two of the most common methods for robot mobility are wheels and legs. Many experimental robots have been developed using both of these methods. This paper makes an overview of some of the robots from each category, both wheeled robots and legged robots, and accounts for the advantages and disadvantages of each. Tracked robots are also covered.

Keywords
Robot, Legged robot, Wheeled robot, Legs, Wheels, Mobility, Continuous tracks

1. INTRODUCTION
Mobile robots have many applications stretching from home entertainment and toys, through military applications, and search and rescue missions where they keep humans out of harm’s way, to the exploration of other planets. One of the most important reasons for their ability to do so is that they are precisely that: mobile. Nonmobile robots, like industrial robots, rarely leave the factory floor.

This paper is an overview of two of the most common ways of locomotion for robots: using legs or wheels. What the respective advantages and disadvantages of legs and wheels are and in what situations each of them is the better choice is discussed.

The main method used in this paper is to give examples of existing robots and analyse how their type of locomotion, either legs or wheels and the number of legs/wheels, affects their performance and possible applications.

After some background to the subject is given, methods for enabling a robot to remain stable is discussed as well as the absence of wheels in nature. Wheeled and legged robots are then covered in separate sections with each section having subsections about aspects specific to each type of locomotion. Both of these sections have a subsection summarizing the advantages and disadvantages of their respective type of locomotion. A subsection about artificial muscles is included in the section about legged robots. Finally, some conclusions are given as well as a short overview of the future of the subject.

1.1 Delimitations
This paper does only consider different types of wheels and legs as well as tracks to some extent. Other locomotive methods such as those used by snakes or hybrid methods such as “whegs” [4] (see Figure 1) are not considered, nor are robots using only one leg [12]. High level actions like obstacle avoidance and path planning are not covered.

1.2 Background
As early as the 1870’s scientists started to investigate how animals walk and run [16]. They even managed to develop some primitive walking models. These were primitive because they moved just as if they used wheels, moving their bodies in a straight path while the legs moved up and down in a mechanical sequence. In the 1950’s it was realized that to get any real advantages from a walking machine over a machine with wheels the legs needed to be controlled individually [16]. The biggest advantage of using legs is the ability to choose where to contact the ground. While a wheel has no choice but to roll over and into every rock, hump or hole in its path, a leg can easily step over such obstacles. One of the early approaches was to utilize a human to control the legs. Succeeding with this was a milestone in legged research as well as the first robots with dynamic stability. Some iconic robots like this are explained in Section 3.

1.3 Dynamic vs. static stability
Stability, or in simple terms: not falling over, is very important to any robot. Since a wheeled or (more importantly) legged robot only has a few small surfaces of its body in contact with the ground (i.e. the robot’s wheels or feet) stability is an issue. The following two subsections are mostly relevant to legged robots, but the reasoning is also applicable to wheeled robots.

There are two ways of ensuring stability: Dynamically and statically.
1.3.1 Static stability
Static stability is defined by [18, p. 38–40] as the following:

An ideal legged locomotion machine is statically stable at time $t$ if all legs in contact with the support plane at the given time remain in contact with that plane when all legs of the machine are fixed at their locations at time $t$ and the translational and rotational velocities of the resulting rigid body are simultaneously reduced to zero.

Where an ideal legged locomotion machine is defined as a machine where "the trunk [the robot’s main body] is modelled as a rigid body, the legs massless and able to supply an unlimited force (but no torque) into the contact surface at the feet’s contact points" which is a good approximation of a legged robot.

The above definition means that the robot is statically stable when its center of mass is within of the support area [18, p. 35], which is the area created by drawing lines between outermost parts of the surfaces currently in contact with the ground (feet or wheels).

When a foot is lifted up from the ground, support area becomes much smaller, as seen in Figure 2, which makes the robot much less stable. If the center of mass comes outside the support area, the robot will fall over if it does not adjust its balance (i.e. use dynamic stability). Some margin must be kept between the center of mass and the edges of the support area in order to handle external forces, such as the inertial forces subjected to the robot if it is moving and then suddenly stops or when it turns.

In order to remain statically stable the robot must therefore only lift its feet in such a way it this does not "shrink" the support area too much. It can only move its center of mass (relatively to its support area) a small distance before it needs to modify the support area (which usually means taking a step).

The advantage of static stability is that since the robot can stop its motion at any time (or slow down, as [18, p. 41] points out), this means that the demands on the control of the robot in terms of responsiveness and precision are much smaller than if dynamic stability is used.

1.3.2 Dynamic stability
If a robot allows its center of mass to come outside the support area, it must in some way compensate for this by for example moving a foot or its center of mass. Since the robot is forced to continuously compensate its balance in order to stay stable (not fall over), it cannot simply stop its motion (or just slow down) for an unbounded amount of time. It might very well be able to stop (slow down or in any other way change its motion) for a short time, but doing so will mean it quickly has to compensate for this.

All of this puts very high demands on the control of the robot. The robot has to:

- Have sensors that measure the orientation and velocity of its body and its limbs with a sufficiently high update rate and precision.
- Calculate how it should move, which has to be done fast enough.
- Move its limbs with sufficient speed and precision.

The advantages of dynamic stability is that it allows for a less restricted pattern of motion, which often means that higher speeds are achievable.

Terrain that is uneven, slippery or contains for example loose rocks or other obstacles often gives difficulties of using static stability. The robot might even be forced to use dynamic stability if it for example slips on a patch of ice or steps on a loose rock that turns over unexpectedly.

Note that a dynamically stable locomotive pattern might very well include intervals that are statically stable.

1.4 The absence of wheels in nature
There are a few examples [2] of organisms that have a body part that can rotate independently of the rest of the body, but all of these are organisms unicellular. Many species use rolling (where the whole body turns) as locomotive strategy but none have a separate part able to freely turn an arbitrary number of revolutions on an axle, which is what is considered a wheel in this paper [13].

This subject is not the focus in this paper so it will only be
The development of the robot was continued and soon it was hard physical labour. For example, carrying heavy loads or doing other tasks that largely resembled the human or an animal body: this can be seen on the drawings of the first manufactured robots. When considering mobile robots, most people would think of multicellular organisms in nature as having continuous tracks. The wheel is also the source of continuous tracks. The embryonic development of animals is inherently different from the manufacturing processes used by humans. It is very difficult, if even possible, for nature to develop a structure where one part is able to turn freely from the rest. All joints in nature have a limited range of motion.

2. WHEELED ROBOTS
From the beginning all wheeled vehicles were unpowered, but during the 19th and 20th century the steam engine and the internal combustion engine were invented. This gave a substantial increase in mobility, both with regard to speed and terrain capabilities [6, p. 337].

The wheel has always been the easiest way to implement mobility in a vehicle, and also the fastest method of travel. Relative to speed it is also the most energy efficient way to travel. The implementation is often very simple, and does not require any advanced techniques such as vector controllers or additional joints to get the robot moving. Therefore, the wheel has since the early 1900 been very popular and it is used in many different robots [3].

Almost every robot is specially designed to perform one or a few specific tasks [14]. Therefore, most of the robots have different designs based and related to its purpose. This means that the propose of the robot decides if it will be appropriate with many wheels to distribute the weight, narrow wheels to achieve higher speed and lower energy consumption or wide wheels for better grip. The track is a related version of the wheel and has an optimization of its active surface and grip to uneven ground. Tracks are used by robots that do not require any high speed or precise movement, but have to get through difficult terrain.

2.1 Implementation of the wheel in robotics
When considering mobile robots, most people would think of an autonomous, mechanical copy of a human body. One can see this in the drawings of the first manufactured robots that largely resembled the human or an animal body: this was the aim of a robot, to perform tasks that humans would typically do. For example, carrying heavy loads or doing other hard physical labour [14].

The development of the robot was continued and soon it was realized that the robot’s look of a human was not entirely necessary, unlike its functions. In 1912 the first autonomous wheeled robot was created, the electric dog named "HM". This robot was, for its time, technologically advanced and could follow a light source that would be considered as "the master" [3].

Figure 3: Using two driven wheels and one free turning wheel. Image courtesy of [25].

The development of the robot was continued and soon it was possible to distribute the weight to as many wheels as possible. This means that the propose of the robot decides if it will be appropriate with many wheels to distribute the weight, narrow wheels to achieve higher speed and lower energy consumption or wide wheels for better grip. The track is a related version of the wheel and has an optimization of its active surface and grip to uneven ground. Tracks are used by robots that do not require any high speed or precise movement, but have to get through difficult terrain.

2.2 Common uses of wheels in robotics
As mentioned, there is a wealth of different designs of mobile robots and other mobile devices [25]. Many of these are wheel-based and their technical design is often chosen based on their specific purposes. This could for example be to handle rough terrain and withstand external destructive influences or to be smooth and energy efficient. For example, the designer may combine the motorized wheels by a number of free-rolling wheels, and also choose between a rigid static chassis and a dynamic chassis with active shock absorbers and joints. These choices affect the number of parts, the weight of the robot etc. Although many factors do matter, such could be the ground clearance and the tire pattern. A general rule is to get as much power from the wheels to the ground as possible.
There are robots in environments where the surroundings do not impose any specific requirements for the robot's mobility, and so the robot will instead be optimized to move as easy as possible. In this case it is easy to implement a double motorized three-wheel system with a balance point (see Figure 3), which may be a bulb or an idler support wheel. The focus is to get the movement as simple and convenient as possible. Such a robot turns by running the right and left motor at different speeds and/or in different directions. The support wheel adapts to the direction of the robot and is only used as a stability point. Such a robot could for example be a vacuum cleaning robot, that works in a terrain that is almost entirely undramatic and smooth. To compare with, if considering a higher level of mobility, a lawn mowing robot is working in an much tougher environment and therefore its requirements are higher. Most lawn mowing robots have four wheels.

A four wheeled system is the most stable considering the number of wheels and its cost to build. This is because it usually has the wheels in each corner at an either rectangular or square shaped platform, without affecting the balance to the same extent as a platform with fewer wheels would.

The generally cheapest, and also the most stable system considering its class with good terrain qualities is the four wheeled platform with constant drive to all wheels, with knobby tires and dynamic suspension and a dynamic chassis. This method is often used where the terrain and the environment require a very high level of mobility. One important consideration is to balance the unit so that it has sufficient ground clearance to pass its obstacles, while keeping the center of gravity low, which reduces the risk of tipping. This problem is partially solved by using larger or higher wheels and putting all of the heavier elements onboard at the base of the robot. There also exists even larger and more advanced robotic system that are used in troublesome environments. These devices can be very heavy, wide or long. This can be compensated either with larger or wider wheels or more wheels, just to get more contact with the ground and distribute the weight over a larger surface.

These examples of robots often use more advanced technology and their capabilities to move across terrain features are often more complex than those of robots with fewer than four wheels. In these cases the robot can be split up into active sections with braces, joints, axes and shock absorbers to reduce the maximum power from the driving wheels to the ground, especially when using a system with a total of more than four wheels. It is very important to design the robot so that the extra wheels as often as possible have contact with the ground in order to get maximum traction. One should keep in mind that if not every wheel is driving and the chassis is static, the system can be more inefficient with more than four wheels and which can cause major problems in hilly or uneven environment. Compare Figure 4 to Figure 5.

The iRobots PackBot [23] is a tracked mobile robot that is made to be a military army unit and its first and foremost function is to do defensive actions. It can be an explosives detector, bomb disposal or for surveillance at dangerous locations. This requires it to have good mobility. The iRobots PackBot was the first robot that entered the Fukushima nuclear plant after it was damaged of the earthquake 2011.

Its design is as follows: the chassis is divided into two unequal sections, were the rear section is the main part. On the rear section it has a couple of tracks and in the front section it has two dynamic pledged "track legs" that can be used as weight equalizer or for extra traction. The combination of these to part gives this robot an increased mobility.

### 2.3 Different choices of tires and wheels

The choice of wheel is also important. When it comes to its type and dimensions the first question is what intended use the robot has, in which environment it is meant to be used, and its size. Generally it could be said that narrow tires are often used in conjunction with a robot that has to have low power consumption and has a low rolling resistance, without encountering any major obstacles. Large wheels with rough patterns are often used on uneven or soft terrain where the tires or wheels get traction by "grabbing" hold of irregularities. There are many variations of wheels, there exist all sizes and dimensions, and all of them have their respective weaknesses and strengths.

A special type of wheels that gives the wheel a new dimension is the mecanum wheel, invented by Swedish inventor Bengt Ilon in 1973 [19]. It has smaller wheels (rollers) along its outer surface at an angle of 45 degrees to the direction of rotation. The special functionality and its technical design makes the mecanum wheel very useful in many cases e.g. in industrial environments. With a combination of four mecanum wheels, a mobile device such as a robot can be driven in all possible directions in the horizontal plane as well as rotate around its vertical axis (enabling a general motion).
The four wheels are placed so that the wheels on the right side are a mirror image of those on the left and the front wheels are mirror images of the rear ones. When the wheels are running against each other the smaller wheels (rollers) start rotating in the same direction and the vehicle moves sideways. If all wheels turn in the same direction the vehicle moves forwards/backwards (see [19] for details).

2.4 Advantages and disadvantages of wheeled robots

The advantages of robotic systems whose mobility platform is built on three wheels (see Figure 3) is primarily that it is a simple to use device, easy to program and is easy to manoeuvre [19]. It is also one of the cheapest statically stable mobile robot platforms, and it does not require many motors or parts. The disadvantages of having contact to the ground at only three locations is that it does not allow the user of the device to have same options for the placement of heavy components or equipment, and will not provide the same stability as a robot with a four-wheeled base. This can cause the robot to become unstable and risks tipping over because of, for example, centrifugal forces when turning. The weaknesses of a three-wheeled configuration are the four-wheeled designs' strengths. A four-wheeled configuration provides an optimal surface area for useful equipment like batteries, motors and controller boards. Weight balancing is easily done and it is not nearly as sensitive to tipping as a platform with fewer than four wheels.

The benefits of the continuous track is that it smoothes out the path and divides the terrain and the obstacles in to a flatten road, and this eases obstacles that could otherwise prevent the vehicle’s movement. The track does also have a much larger active surface to the ground, which generates more grip compared to what a wheel or leg does. This platform configuration is easy to navigate and turn, but does not have a comparable mobility in speed compared to wheels, and it generally uses more power when it has more internal friction, and also weighs more.

A wheeled robot can be built in such way that its chassis is lower than the top of the wheels, which means that if it falls upside down it can still drive the same way it does upright [11]. See Figure 6.

3. LEGGED ROBOTS

3.1 Statically stable platforms

The first walking robots were statically stable for natural reasons, statical stability is the easier alternative. A statically stable robot can be controlled slowly and will work just fine without any sort of balance sensors. As early as the late 1800 century people tried to mimic animal walking with machines. An example of this is the sketch in Figure 8 from 1893 showing a mechanical horse [20]. This type of machines using a fixed type of walking pattern would not really give an advantage over a wheel. To get a real advantage from a walking machine the legs have to be controlled separately.

To be able to separately control every leg and to choose its support is called to use a free gait. Some of the first walking machines that had the ability of free gait were controlled by a human in a harness. An example of this sort of machine was built in the mid-1960’s by Ralph Mosher [16]. It was called the "walking truck" and was a close to 3.5 meters tall hydraulically powered beast. Weighing almost 1400 kg, this machine with its human operator could push cars out of the way and climb piles of rail road ties. The most amazing was that its legs had advanced force feedback that allowed the operator to control them with great accuracy. Although this machine worked it was very tiring and demanded full concentration of the operator to control all the legs at once and move them in correct order.

The solution came with better computers. When a computer could take care of the exhausting problem of coordinating the legs, the science of walking machines got to a new milestone in history. In the 1970’s Robert McGhee’s group at the Ohio State University built the first successful computer controlled hexapod robot (Figure 7) [16]. This robot had six legs and was very slow. The main task of the computers was to coordinate the 18 motors, making a number of different types of gaits possible while always keeping the center of mass in a stable position. The problem with this approach is though that having 18 engines mounted in the leg joints, and needing to solve advanced calculations for every move, is both power and time consuming as well as expensive.
3.2 Energy efficient crawlers

Shigeo Hirose, a professor at the Tokyo Institute of Technology, realized that to get the most out of a statically stable crawler it needs to have lightweight legs and a more efficient way of locomotion. He combined the early mechanical leg approach with modern computers and actuators. This made lightweight legs and a much simpler way of control possible. He designed the legs like a three dimensional pantograph (see Figure 9) that made it possible to use just one actuator at the time to get the leg to move in a predictable way [1]. To be able of just choosing one actuator to get an x, y, or z movement of the leg freed the computer of the heavy motor coordination calculations. Two actuators attached to point Q will allow point P to move freely in the plane, and a third actuator attached to point R will give the leg freedom to move up and down in the n direction. Combining this design with the wire and foot design, shown in the picture, will make the foot part stay at the same angle regardless of how the leg is positioned.

He also implemented the theory of Gravitationally Decoupled Actuation (GDA) to his robots. GDA is an energy efficient and simple strategy for movement. Instead of wasting power by having joints that work against each other, the actuators are placed so that the force they put out goes only into efficient movement. In theory, an object that is moving at constant speed over ground and keeps it center of mass at a constant height is not performing any work and therefore demands no energy.

The difference is easiest understood by studying Figure 10 that shows the movement of one ordinary leg and one using the GDA principle. In the non-GDA mechanism the two joints \( a1 \) and \( a2 \) must both generate torque and angular velocity to create motion. Thereby this design requires power even under the ideal theoretical condition that the legs have no mass.

In the GDA design the actuator \( b1 \) only needs to generate velocity (move the robot) but no force. The actuator \( b2 \) only needs to generate force (carry the robot’s weight) but no velocity. Under ideal condition this design does not need any power to move. This is theoretically explained by the fact that energy equals force multiplied by distance travelled, keeping either the force (in the case of \( b1 \)) or the distance travelled (in the case of \( b2 \)) equal to zero results (in theory) that no energy is used.

However, since the mass of the legs and the acceleration cannot be zero, and since there exist friction, even this design requires power. However these can be assumed to be quite small if the legs are light and don’t lift the feet very high.

3.3 Dynamically stable robots

The main problems that the crawler has are that they are heavy, slow, and have many moving parts. A robot that can actively balance itself does not need to have a lot of legs. This makes the robots lighter and more practical. Faster and smaller computers have made the early problems with balance much easier to solve. This also opens up for the possibility of a robot to perform short states of ballistic flight such as jumping or running. With balance the reach of the legs can be extended and it is possible to compensate for
acceleration by moving the center of mass relative to the support area. Balance makes it possible to jump over obstacles or to use a very narrow support area. The first kind of running robots were one legged [12]. The definition of running is that the object should perform a period of ballistic flight between every step [16, p. 7]. The idea was that if this problem could be solved for a one legged jumping robot the solution could be transferred to a multiple legged machine.

### 3.4 Examples of legged robots

#### 3.4.1 ASIMO

Even though robots that use balance are rare in everyday life today, they do exist and actually work rather well. One of the best two legged robots today is ASIMO, made by Honda Motor Co [8, 9]. This humanoid robot has 34 servos and can climb stairs, run, walk and maintain balance if pushed or impacted to a certain degree. It has stored motion patterns of walking, turning, running and start/stop that it can combine with sensor data in real time and change actively by predicting its next motion. It also shifts its center of mass in real time to be able to turn while walking. When the robot moves it is influenced by gravity, and forces from acceleration and deceleration. Together these forces make a resulting force vector that is called the total inertial force. To maintain balance the robot has to support its center of gravity in the opposite direction of this force at all time, this opposite force is called the **ground reaction force**. When these two forces for some reason do not align the robot is out of balance and needs to somehow realign these vectors before it falls. The point that the total inertial force intersects the floor at is called the **zero moment point (ZMP)** and the point where the floor reaction force operates is called the floor reaction point. The computer calculates a theoretical walking pattern and the servos move according to this until something unexpected happens and these two points don’t match up. For example, if a rock would get under the front part of the foot the floor, the reaction point would be misaligned with the ZMP point and the robot would tend to fall backwards. To compensate for things like this ASIMO has three control systems that work together [9].

**Floor reaction control** is the first one of them. It controls the angle of the feet on uneven surfaces. In the case that something, like a rock or a doorstep, gets under the front part of the foot, the floor reaction point would be further forward than the ZMP. To compensate for this, the control lowers the back part of the foot to move the floor reaction point backwards and regain stability.

**Target ZMP control** accelerates the upper torso in the direction that the robot threatens to fall. If the object under the foot is big enough, or the floor reaction point and ZMP for some other reason is so much misaligned that the floor reaction control cannot compensate enough to realign them this function kicks in. If the robot for example is about to fall forward this control would accelerate the center of mass forward and thereby creating an opposite force to the fall. When this happens the third system **Foot planning location control** compensates for the irregularities caused by the target ZMP control. The originally planned position for the next step is adjusted to catch the new position of the center of mass so that stability is regained. Being this advanced has its disadvantages though, 34 servos (12 for the legs) mounted in the joints consume a lot of power. In one hour it will drain it 6kg lithium ion battery. ASIMO is also extremely expensive due to its many servos and expensive materials needed to keep its weight low.

#### 3.4.2 Big dog

ASIMO is built to work in a home or office environment and cannot yet handle any hard terrain. There is however a four legged robot today that can. Boston Dynamics has with funding from the Defense Advanced Research Projects Agency (DARPA) built a four legged platform called BIG DOG [17]. BIG DOG has one big design advantage over ASIMO. Since ASIMO uses electrical motors for all its joints, it can never be as fast as a real animal. BIG DOG on the other hand is powered by hydraulics. Hydraulic actuators are much faster and stronger than electric servos and this makes BIG DOG able to compensate for bigger and faster unexpected changes in the environment. With a weight about 109 kg, and length and height of about one meter it is the mechanical horse that science fantasized about in 1893. It can also carry over 50 kg of load through almost any kind of terrain and 150 kg on flat ground [17].

Each leg uses four hydraulic actuators with sensors for joint position and force. It can jump and run and maintain its balance on loose and slippery grounds like ice or gravel, and it can climb hills up to 60 degrees. In similarity to ASIMO it can actively move its center of mass while walking to get a seamless natural type of movement. It also changes its height and attitude to fit the terrain like leaning forward while climbing slopes and backwards while descending [17]. This is a truly remarkable machine but the hydraulics also have a disadvantage. To get the pressure in the hydraulic system it is powered by a 15 horse power 2-stroke engine that makes the robot as noisy as a motorcycle.
3.5 Advantages and disadvantages of legged robots

To have a platform with legs that are able to strategically choose contact points on the ground is a vast advantage over wheels in many ways. Not only because of the previously mentioned reason that it can step over obstacles, but also for the fact that it can move smoothly over terrain. Consider a statically stable robot that moves one leg at the time and gently places it at a new stable position, the main body of such a robot would float forward smoothly like a boat, even on really rough terrain like in a forest. Another advantage is the ability to change direction of movement without changing the direction the body is facing. This is useful in tight spaces and creates a faster and more natural movement in places with a lot of obstacles. Wheels also have a tendency to slip on the ground when they lose traction. A leg on the other hand is much kinder to the surface it moves over. It can distribute its weight and even move its center of mass without changing the positions of its supports [1]. This advantage is desirable in cases like moving up or down a slope or stairs, or where there is a long distance between supporting objects to step on.

The advantages are not just noticeable in rough environments. The urban society of today is in many ways adapted for legs: Ask anyone in a wheelchair. Urban obstacles like stairs and doorsteps are often a problem for wheeled platforms. All these possible advantages come at a price though, the design will be more complicated and will have more moving parts. While a robot with wheels could work just fine with only two motors, one for forward trust and one for steering for example, a robot with legs needs at least tree actuators for each leg if one wants it to be more useful than a wheel. The actuators used today are still heavy compared to their power output. This often makes legged robots very heavy or weak, especially if they have many legs.

3.6 Artificial muscles

As seen above, the science of legged robotics has gotten a long way but still has some problems to solve, mainly the power to weight ratio and the speed of the systems. Hopefully the missing part of the puzzle can be the development of artificial muscles. This science is very new, but it exists already. One approach to the problem is Electroactive Polymers [26]. This is a material that can be shaped in many ways and when stimulated with an electric field they change size or shape. With this material it is possible to build anything from very small and light actuators to larger more advanced tentacle like structures. Another approach to creating a artificial muscle is to the McKibben Pneumatic Muscle [5], seen in Figure 11. It is a pneumatic bladder that has fibres running on the outside. When pressurized, the muscle attracts just like a natural muscle. This solution is cheap and very lightweight and it also has a natural compliant behaviour. When an outside force is pulling on this pneumatic actuator it gives in a bit while still keeping the force constant. This is an advantage in many cases and gives the linkage it controls, e.g. a leg, a natural flex. Artificial muscles are probably the future in robotics and will hopefully make legged robots cheap and practical enough to replace wheeled platforms in many places. No advanced variable walking robots like those mentioned above have yet (to the authors’ knowledge) been built using artificial muscles, but there is at least one jumping robot that has. It is developed in Japan and is named Mowgli [15]. This frog-like robot has six pneumatic muscles, weighs approximately 3 kg and is about 0.9 meters long with its legs extended. Mowgli can manage to jump 0.5 meters high and land softly. This is more than 50% of its own body height, which for a robot with multiple-degrees of freedom using legs is extremely good performance. It has touch sensors on its foot to e.g. potentially detect touching at each joint and a pressure sensor on each muscle. The natural compliance that the muscles give ensures a soft but firm landing and the balance during the jump is modelled after the well-known algorithms of balancing an inverted pendulum with a lumped mass [21].

4. CONCLUSIONS

The reason for the diversity in techniques and technologies for robot mobility is apparent: Each way of giving a robot its mobility, whether it is with wheels or legs (how many wheels or legs), statically or dynamically stable etc., has its own set of advantages and disadvantages. Since the number of possible applications and uses of mobile robots is so huge, no single way will ever be seen as the overall best. However, some conclusions can be drawn.

In general, wheels are more energy efficient than legs on flat surfaces with good traction. Wheels are also often a cheaper alternative to legs, since they are simpler to design and have far fewer moving parts. This simplicity makes low level tasks such as simply moving forward and steering trivial, the same is not always the case when legs are used. The examples in this paper show that legs have the advantage of enabling the robot to choose where to put its feet which is very handy in rough terrain, as opposed to a wheels that simply roll over whatever that comes in front of them and get stuck if they cant roll over the obstacle. In some types of terrain there are often only a few sections of the ground that provide a stable foothold with the rest of the ground being either too unstable such as loose rocks or too soft and slippery such as mud. This means that a legged robot can often only traverse this type of terrain if it can select where to put each of its legs as opposed to legged robots that move there legs according to a fixed pattern. The ability to do this, as well as deciding where to put each foot, is though a difficult task.
The above indicates that a robot that has legs that it cannot control individually will have the disadvantages of legs (the cost, mechanical complexity, difficulty of control etc.) but not the advantages over wheels (terrain capabilities etc.). This would suggest that legs should only be used if the robot will have the ability to choose where to put individual legs. As opposed to use legs that move according fixed pattern, where wheels should be used instead.

4.1 The future

As seen in the sections about the ASIMO and Big dog robots, the techniques for using dynamic stability have come a long way. However, most animals are still a long way ahead in many aspects.

Even though some robots are built to work in dirty environments like forests or muddy terrain, like Big dog for instance that has been tested in both mud and snow, many robots are to a high degree developed to work in a laboratory environment. Dust, moisture, foreign objects etc. will severely damage most robots of today. To make a robot that is capable of working outdoors (or indoors for that part, there are many indoor environments, e.g. industrial, that are very dirty) it will have to have some kind of protection of its sensitive parts (circuit boards, connectors, the inside of motors etc.) from foreign objects, dirt, moisture etc. This is of course easier to do on wheeled robots since these generally are simpler in their design.

Depending on the environment, the internal temperature of the robot might also have to be regulated in order to protect its sensitive parts. A minimum is that the robot’s sensitive parts must be made to handle the temperatures the robot is expected to experience.

As mentioned in Section 4, the ability for a legged robot to choose where to put its feet is essential to its ability to traverse difficult terrain. Big dog is an example of robots that have this ability and makes good use of it. This ability is though not easy to accomplish and most legged robots use instead a fixed pattern to move their legs which greatly reduces the advantage of legs over wheels. A lot of work remains in creating techniques to enable robots to distinguish places of the ground that are appropriate, choose which of these places to put their feet and finally to move its feet to these places. These abilities would most likely require sensors that evaluate the ground from a distance (i.e. cameras, LIDAR etc.) as well as a very precise control of the robot’s legs and balance.

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