Ranger Robot

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***Abstract*—The Ranger Robot is based on the approach of dynamic walking. Although it has already been shown that dynamic walking works in practice, it has never been shown that this method is reliable for walking a long distance. On April 3 2008, the Cornell Ranger walked a world record distance of 9 kilometers. It is the first walking robot to walk such a distance without being touched by any person, and without replacing or recharging the batteries.**

Fig. 1. The Ranger robot during the record attempt

I. INTRODUCTION

Research into walking biped robots lets us increase our understanding of human walking, in both healthy and impaired people, and learn us learn to build better service and entertainment robots and prosthetic devices. Builders of most of the well known walking robots, such as Honda's Asimo [1] and the HRP robots from the METI humanoid robotics project [2] started with tight position control of the limbs and static balance on wide flat feet, then tried to find motions which would allow their machine to take steps while still maintaining balance. The resulting motion, however, lacked the grace and economy of effort seen in human walking. Taking a different approach, other researchers have developed mechanisms and controls that enable dynamic walking in their robots. Such as Denise [3], Cornell Powered Biped [3] and Runbot. These bipeds are analyzed and designed as dynamic systems; the motions required for walking follow from the mechanics. Maintaining static balance throughout each stride is not required; they walk by falling forward while standing on one foot, catching themselves by swinging the other foot forward, and falling forward again. This last method is called dynamic walking and has two advantages compared with the first method. These advantages are: low energy use and human like movement.

Cornell University and Delft University of Technology have built various prototypes [4], [3], [5], [6] using this type walking. One of the Cornell prototypes showed the good energy efficiency of dynamic walking by walking with only 11 watt [3]. This energy consumption is similar to humans when scaled with the mass and speed. (see chapter V)

Although it has already been shown before that dynamic walking works in practice , it has never been shown that this method is reliable for walking a long distance. In April 2008 the Cornell Ranger walked little over 9 kilometers without being touched by any person, and without replacing or recharging the batteries. It is believed that this was a world record at that time. (RHex walked 2.5 km, Big Dog walked 6.5 miles but with refueling. [7])

A long uninterrupted walk requires at least least the following properties:

- reliable mechanics and electronics
- energy efficient movements
- a way of steering, to not be dependent on a long straight surface.

This paper presents the design of a robot with these three properties, and the enhancements made to be able to walk a longer distance as in an earlier record attempt (December 2006).

II. MECHANICAL DESIGN

The main principle used by the mechanical design of the robot is: keep it simple. The idea is to reduce the chance of failures by keeping the design as simple as possible. The 'keep it simple'-principal can be seen in the limited amount of degrees of freedom and actuators. The robot is a so-called four-legged biped. This means that the robot has two pairs of legs, an inner and an outer pair. The legs of each pair are rigidly attached to each other and both pairs are connected at the hip with a hinge. Due to the four legs the motions of the robot are more or less constrained to a 2d-plane.

Figure 2 shows a CAD-drawing of the robot. The robot has a mass of 8.5 kilograms and a leg length of 1.014 meter measured from the bottom of the foot to the hip. There are three degrees of freedom, one at the hip and two at the ankles. Each of these degrees of freedom is actuated with a separate dc-motor. The robot has no body, the legs hinge with respect to each other at the hip joint.

A. General lay-out

The motors and the other heavy parts (i.e. batteries) are located around the hip, in order to get the center of mass of the legs as close as possible to the hip. This is done for two reasons: (1) to minimize the inertia of the legs with respect to the hip joint and (2) to get good dynamic symmetry between the two pairs of legs.

The low inertia of the legs is important for the energy efficiency, because the hip torque needed to accelerate the swing leg is almost linear with the inertia around the hip. Also a low inertia of the swing leg is useful for the control, because with this low inertia the movements of the swing leg do almost not influence the motion of the stance leg.

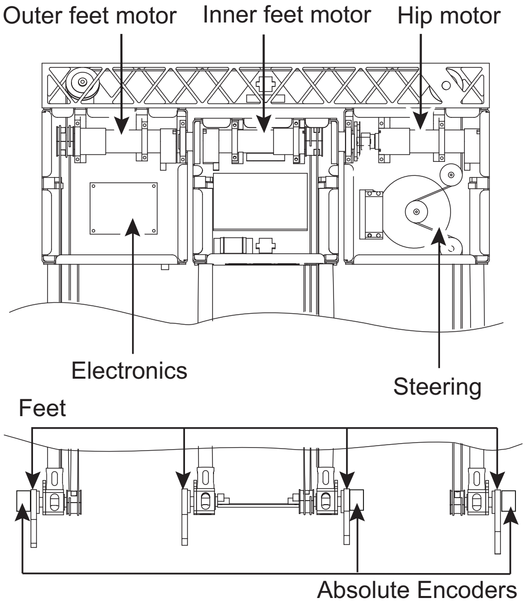

Fig. 2. CAD-drawing of the Cornell Ranger and its most important parts

B. Hip and feet actuation

The hip and both pairs of feet are actuated with nominally 46 watt dc-motors (Faulhaber #2657CR012). The hip motor is equipped with a 66:1 planetary gearbox (Faulhaber series 30/15) and both feet motors have a 43:1 planetary gearbox (Faulhaber series 30/15). The hip motor is located in the outer leg and its shaft is attached to the inner leg with a flexible coupling. This flexible coupling allows for some misalignment between the hip bearing mounts and the motor mount.

The feet are connected with a cable system to the motors (figure 3). In this cable system there is a spring to keep tension on the cable and another spring to reduce the spring force on the motor. The springs have a low spring constant and a high pretension, so that they behave almost like constant force springs.

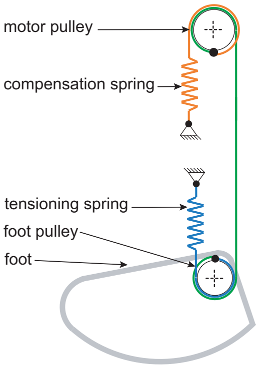

Fig. 3. Cable system used to actuate the feet

The inner feet are rigidly connected so that they can be actuated by one cable. For the outer feet two cables are necessary to actuate the feet (figure 4).

C. robot symmetry

1) dynamic symmetry: The legs are dynamically symmetric if they move the same when the same force is applied to both and if the complete robot will move the same irrespective of which leg is in front. In order to be symmetric the legs should have the following properties:

$$I_{outer,hip} = I_{inner,hip} \tag{1}$$

$$m_{outer}c_{outer} = m_{inner}c_{inner} \tag{2}$$

$$m_{outer}d_{outer} = m_{inner}d_{inner} \tag{3}$$

in which I_{hip} is the inertia around the hip, m is the mass, c is the vertical distance between center of mass and hip and d is the horizontal distance between center of mass and hip. The above properties can be fulfilled without the legs having the same mass.

Since the robot was built in December 2006, mass has been added to the robot (in the form of batteries) in order to improve the dynamical symmetry. This is desirable since a completely symmetric robot is easier to control (same control action for both legs).

2) cable symmetry: Another challenge in the robot is that not al the cables have the same length (figure 4), effectively influencing the control of the feet. Initially, we assumed that the cables were stiff enough to ignore compliance in the cables. (The stiffness of the cable is $4.1415e + 004\frac{N}{m}$) In practice, the cables actually behaved like springs. Because of the springlike behavior of the cables, the response of the different feet differed. The resulting stiffness around the different ankle before the cable adjustments:

$k_{torsional-left-anklejoint} = 3.6\frac{Nm}{Rad}$
$k_{torsional-right-anklejoint} = 5.8\frac{Nm}{Rad}$
$k_{torsional-middle-anklejoint} = 6.1\frac{Nm}{Rad}$

Besides the cable length differences, the actuation of the inner feet was off because the two inner feet were activated by only one cable. This means that the stiffness of this cable ideally should be twice the stiffness of the cables going to the other feet. By placing rigid parts at multiple places in the cable the stiffness of the cables has been made symmetric.

The resulting stiffness around the different ankle after the cable adjustments:

$k_{torsional-left-anklejoint} = 6.44\frac{Nm}{Rad}$
$k_{torsional-right-anklejoint} = 5.8\frac{Nm}{Rad}$
$k_{torsional-middle-anklejoint} = 13.32\frac{Nm}{Rad}$

Since there are sensors at both the feet of the robot and at the motor of the robot, in principle it is possible to use the stiffness of the cable in order to estimate the torque applied without adding regular springs, leading to Series Elastic Actuation [8], but this feature was not used for this paper.

D. Steering

Steering for the robot is necessary in order to walk a long distance without a long straight track. The simplest way of making the robot steer is to create some asymmetry in the outer feet of the robot. This can be done for the outer feet by changing the length

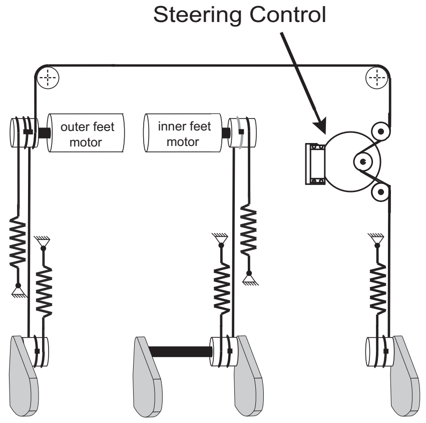

Fig. 4. Cable system for the inner and outer pair of feet

of one of the cables between the motor pulley and one of the foot pulleys (figure 4).

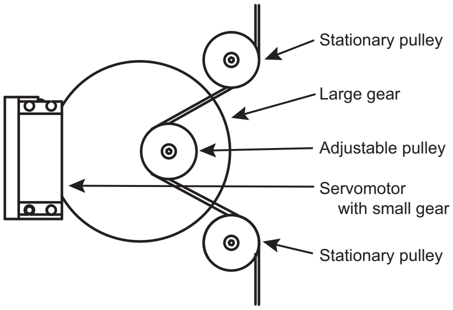

Fig. 5. Steering system

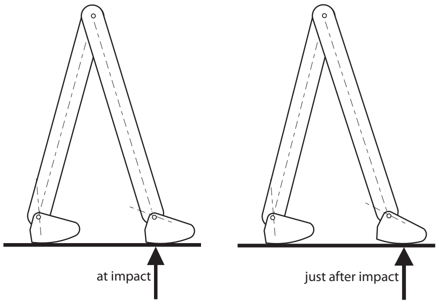

Fig. 6. Steering rotating the foot down after impact

This was done with the mechanism in figure 5. This concept uses two gears. A small gear is mounted on an rc-servo motor and a large gear is mounted on the robot. On the large gear a pulley is eccentrically mounted, so that by rotating the large gear the length of the cable can be adjusted. The gear ratio between the large and the small gear makes the system non back drivable. Making the steering foot angles a-symmetric is not enough to make the robot go around a track. In order to let it steer better, the robot rotates the feet a little bit down just after impact. (figure 6) It is hypothesized that since one of the outer feet one foot will hit earlier and slaps the ground after impact, more energy is dissipated from this leg. This results in a net moment around the robot. Whether this is the actual the mechanism which makes the robot steer is not certain at this point. From testing it followed that without rotating the the feet down after impact, the robot doesn't steer.

III. DATA ACQUISITION

The robot has a wireless interface for communication between the robot and a computer. During the record attempt this connection was only used for data collection.
During testing the wireless connection was also used to tune parameters on the fly, to test settings without reloading software to the robot all the time.
The data acquisition exists of a wireless connection sending out 8 data channels every 16 ms and an additional 8 data channels every 128 ms. The data is processed by a labview program, showing the values of the selected channels. If desired it is possible to log all the data to plain text, having it available for processing afterwards.

IV. CONTROLLER

The controller can use the following sensors:

- incremental encoders on all three motors.
- absolute encoders on all the robot joints.
- inertial measurement unit (IMU).
- contact sensor in each foot.
- battery voltage sensor.
- current sensors for battery current and for motor currents.
- ankle limit switches.
- potentiometer on the steering mechanism.

A. *Overview of the behavior structure*

The behaviors are being designed as in figure 7. The main blocks for this are:

- State machine, determines whether there is a state transition
- Parameter Determination, if there is a state transition the parameter determination function determines the policy

The policy determined in the set functions contains parameters which are sent to the controller in order to get the desired control. Separating into these three blocks ensures that the software code remains readable even when the control gets more complicated.

1) State Machine: There are three separate state machines in the robot at the walk controller level. One for each pair of feet, and one for the hip activation. The two separate state machines for the inner and outer feet are identical. The main advantage of having multiple state machines is the reduction in the total amount of states, and a more readable code.
2) Calculation of Control Parameters: The parameters used in the control of the robot are not fixed. During each state transition the control values for the next state are computed. This is done in the Calculation of Control Parameters block. The calculations are based on the complete dynamic state of the robot. This can be seen as feedback which occurs only a couple of

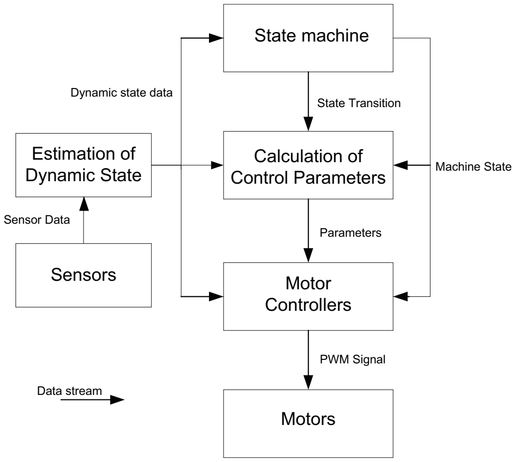

Fig. 7. Data streams in the Ranger robot

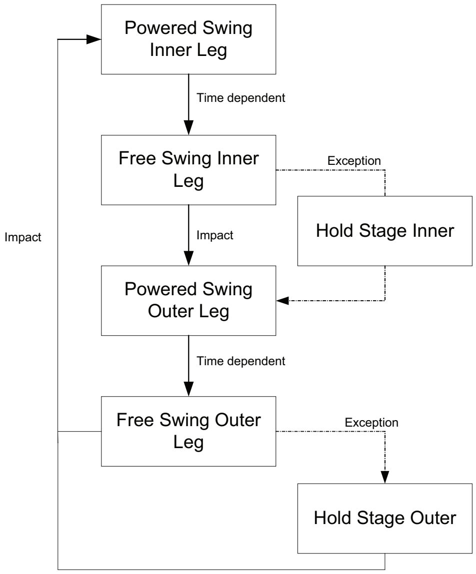

Fig. 8. Hip State Machine

times per walking cycle. At the moment the following quantities are determined in this function:

- push off angle of the feet
- desired hip signal

B. walking stability

In order to be able to walk a long distance it is necessary to have not only a robot which is energy efficient, but also stable enough to overcome small perturbations. (Although the robot walked on a indoor running track, the track isn't completely level/smooth.) Although there shouldn't be a trade off between stability and energy use, in practice it is easier to have a very stable walker when there is less of a penalty on the energy usage. Measures taken to let the robot walk stably were:

- let the robot walk at sufficient speed all the time, diminishing the chance that it isn't able to get over midstance (stanceleg having a 90 degree angle with respect to the horizontal).
- try to approach a ”preemptive” push off, so no push off is needed after heelstrike. Because of the lack of knees, it is important to get the feet out of the way to prevent scuffing.
- use of swing leg retraction, further discussed in the next paragraph.

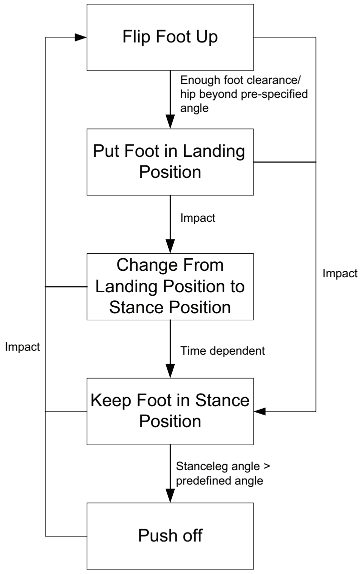

Fig. 9. Foot State Machine, used twice for both inner and outer feet

C. leg swing control

The controller in the Ranger Robot is designed such that the controller exploits the dynamic properties of the complete robot, including the drive train. To be able to let the legs swing smoothly in their natural frequency, the legs legs are only actuated for a limited time, after that no actuation is used and the legs are able to swing freely until impact. This means that the input signal desired to get the correct motion has to be computed in advance, since there is no feedback used during the swinging of the leg.

The signal needed to swing the leg can be computed when the robot is in double stance phase. At that moment of time the angular velocity of the hip joint is assumed zero, and the angles of the legs are known. The input signal to the hip motor is based on the angle of the swing leg with respect to the vertical. The swing leg is actuated such that the leg will go past the desired angle, and then falls back, crossing the desired angle after approximately 0.65 seconds (figure 10). This is known as swing leg retraction.

From literature it is known that using swing leg retraction improves the stability of a walking biped. This phenomenon was observed by Seyfarth [9] for running and by Wisse [10] and Hobbelen [11] for walking bipeds. Besides the swing leg retraction, it was desired to let the legs swing in their natural frequency and to prevent any hold stages in the control to ensure a smooth motion, and energy effectiveness. The signal which goes to the hip motor is based on the angle of the leg at the start of the swing phase, as well as on a desired step length (expressed in a desired angle). For this the following equation is used:

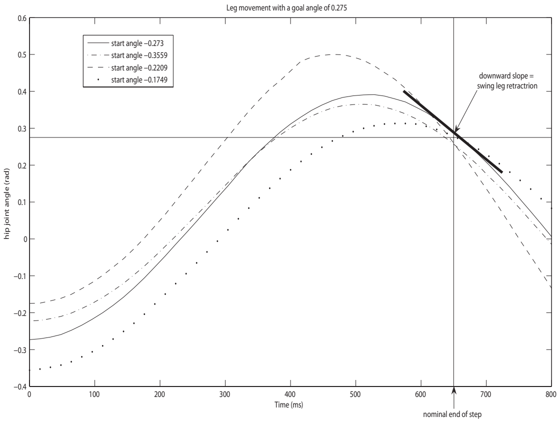

Fig. 10. Leg movement in a benchtest which enabled the legs to swing freely

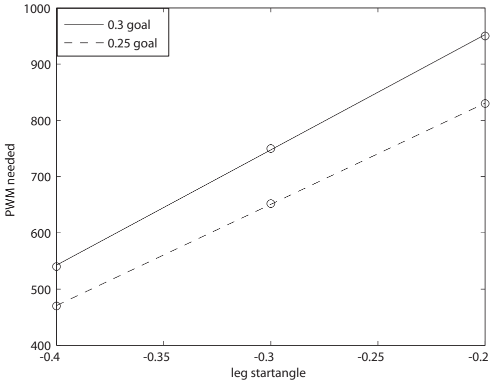

Fig. 11. needed pwm signal in order to reach the desired goal angle after 0.65 seconds

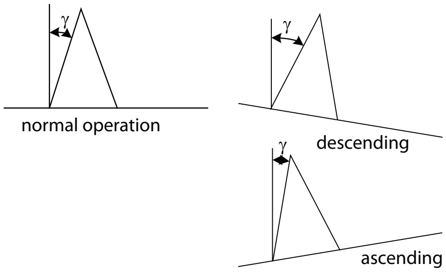

Fig. 12. Input Angle for Swing leg control

$$PWMmax = k(\phi - \phi_0) + C_1$$

In this:

ϕ = starting angle of the leg with respect to the vertical
k = determined by the goal angle
C_1 = fitted from benchtest data
ϕ_0 = angle at which the linear approximations cross each other

ϕ_0 can be found by interpolating the two linear functions found in figure 11. For each goal angle there is a linear approximation starting at ϕ_0, with only a different slope. A relationship for the slope of each linear approximation can also be found from figure 11. It is assumed that the slope changes linearly between the two found linear approximations. Therefore the slope of a linear approximation can be written as a function of the goal angle:
$k = m(goal - g_0) + C_2$
In this:

g_0 = the goal angle used for lowest approximation (0.25)
m = rate of change of the slope.
$goal$ = the desired goal angle, defined by the user.
C_2 = constant fitted from the data.

Only the intensity of the applied signal is changed, while keeping the same shape of the actuation pattern. Since the hip control is based on the swing leg angle with respect to the vertical, an increase of the angle results in the decrease of the energy input of the swing leg.(figure 12) This means less energy is going to the leg swing when walking slightly downhill, and more energy is going to the legs when walking uphill. Since (although small) the legs have some weight, this helps to get the robot over mid stance. Because the robot will slow down walking uphill, the step size will still decrease.

As can be seen from the state machine structure there is a hold-state in the controller, this state is only to prevent the robot from making steps which are too small. When the robot takes steps which are too small it can trip.

If a step takes to long to complete, the leg will fall back to far (since it is an uncontrolled motion). In order to prevent this, the robot controller will fix the angle between the legs, this is done in the hold-state. (figure 13 During normal operation (walking straight forward) this state isn't visited.

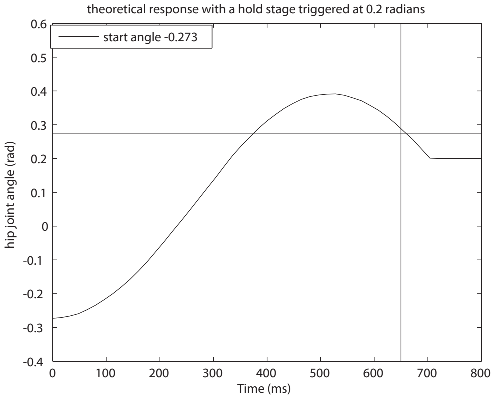

Fig. 13. Hold stage (theoretical)

D. foot control

The feet of the robot are controlled by a proportional position controller. During the stance phase the feet are kept in a more or less neutral position. This means that the feet are kept in an angle such that there is only little moment around the ankle joint, therefore the ankle can be controlled using low gains. In order to let the feet land at the right angle, the landing angle is defined with respect to a fixed coordinate system (based on IMU data).

In order to walk energy efficient it is tried to approach a preemptive push off. This isn't actually realized since the push off takes place a little early to make sure that there is a push off before heelstrike. Using a push off while between midstance and heelstrike gives the possibility to flip the feet up at heelstrike of the swing leg. This diminishes the chance of scuffing the foot.

The feet of the robot are flipped down as soon as there is enough room to flip the feet down, based on IMU data, and when the swing leg is beyond a certain prespecified angle.

V. RESULTS

On April 3, 2008, the robot walked just over nine kilometers (±9075 meters according to the distance measurement on the robot). After walking 312 minutes the robot fell back because of low battery power.

The record was set on a rubberized indoor running track. The robot had to walk 45 laps in order to travel the nine kilometers. At the time of the attempt this was a new record for a walking robot. The average stepsize during the walk was 0.33 meters, and the average speed was 1.75 km/hour.

In order to walk a long distance with a battery powered robot it is important that the robot walks energy efficient. This efficiency can be expressed in the cost of transport. The cost of transport (Cot) is defined as: $c_{et} = \frac{E_{used}}{m*g*d_{traveled}}$ In order to get a low cost of transport the robot walks using its own dynamical properties instead of controlling all the joints. This is insipired on the ”passive dynamic” walking introduced by McGeer [12]. This class of powered walkers is also known as dynamic walkers.

The robot walked a total of 9378 meters before it stopped working.(Before the start of the record attempt a small test walk was performed in order to check whether the robot was functioning correctly.) The average battery voltage during the walk was 11.14 volts (from the robot data acquisition). The 9378 meter consumed 130.5 Watt hour, this figure based on the amount of energy available in the batteries before and after the record attempt. This means that the robot had an average energy use of 25 watts, and a cost of transport of: $\frac{E_{used}}{m*g*d} = \frac{130.5*3600}{8.5*9.81*9078.8} = 0.6$

In comparison the Honda Asimo has a Cot of 3.2, [13], the Cornell Powered Biped has a Cot of 0.2 [3], T.U. Delft Denise has a Cot of 5.3 [3] and a human has a Cot of 0.3 [14].

The main energy consumption of the robot is not in doing mechanical work, but in maintaining positions. Using knees could decrease the energy use significantly since it then is possible to give the feet a preferred position.

During testing in the lab it was possible to let the robot walk for a total energy use of approximately 10.5 Watts, of which approximately 5 Watts was used for electronics. When walking with this amount of energy consumption the robot walks very slow. With the current controller the robot walked over 0.6 m/s at a total energy consumption of 17 Watts.

A huge amount of energy consumption is in the feet of the robot, because of the design of the feet there is no preferred (stable) position when in stance phase. As a result of this the feet have to be controlled throughout the stance phase. This results in an increased energy usage. A second reason for the energy consumption of the feet is the maintaining of an elevated position after push off, in which a high electrical cost is involved, but no mechanical work is done. This part could be improved by timing the push-off better. However since the actual moment of impact is not known, the space for improvement is limited. In order to improve efficiency more (optimize the cost of transport) the energy stored in the cables could be used by extending the push off after heel-strike. This however can give scuffing problem because of the lack of knees.

VI. CONCLUSION

This paper describes the design of the Cornell Ranger. A robot build to show that it is possible to make a reliable walking robot using the dynamic walking method.

To reach this goal the following requirements were set:

- reliable mechanics and electronics,
- energy efficient movements,
- a way of steering the robot.

The mechanical design was kept as simple as possible in order to get reliable mechanics. All the heavy parts were concentrated around the hip to reduce the work needed to swing the leg and to get a good symmetry between the legs. The robot was designed with three internal degrees of freedom (one hip and two ankles). All these degrees of freedom are actuated with dc-motors. For the ankles a cable system is used to transfer the power from the motors to the ankles.

The robot is steered by making an asymmetry in the feet actuation of the outer feet. The steering system is made up by a non back drivable gear system, an rc-motor and an rc-controller. The system is energy efficient, because it only uses energy for changing the steer angle and almost no energy for holding it in place. The control of the steering is also reliable, because of the use of a widely used and reliable rc-controller.

The robot reached its goal and showed that a walking robot can walk reliable with using the dynamic walking method. And there is still room for improvement, so there is a promising future for this robot and dynamic walking robots!

VII. ACKNOWLEDGEMENTS

This project was a team effort. More than 18 people worked hard to make this project a success:

Gregg Stiesberg, Pranav Bhounsule, Rohit Hippalgaonkar, Leticia Camargo, Carlos Arango, Megan Berry, Alex Gates, Matt Haberland, Sam Lee, Andrew Mui, Andrew Spielberg, John Buzzi, Avtar Khalsa, Andrey Turovsky, Stephane Constantin, Ben Oswald.

VIII. APPENDIX: DESIGN DETAILS

A. details on the mechanical design

1) Supporting structure: The outer legs are constructed out of two sheet metal boxes and a top bar connecting the two boxes. The inner leg is constructed out of one box (figure 14). Boxes are used because they are light weight and relatively stiff.

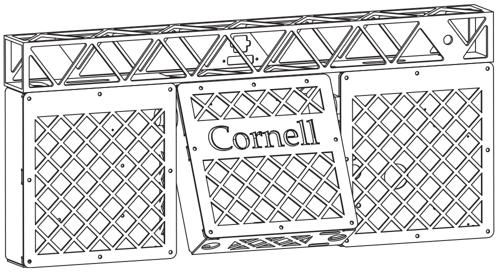

Fig. 14. Supporting structure made of three boxes and a top bar

2) Ankle joint design: The ankle joint for this robot was a challenging part to design, because it has a tight weight limit (maximum 100 gram) and it has a complex function. The ankle has the following functions:

- a rotational joint between the leg tube and the foot,
- a stop to limit the motion of the foot,
- a guide for the sensor wire from the foot to the leg.

Figure 15 shows a half section of the ankle design. The shaft is partially hollow and has a opening in the middle so that the sensor wire can go from the foot into the hollow leg tub. The sensor wire is wrapped around the shaft one time to allow for rotation of the shaft. The shaft is supported by two flanged bearings. These bearings are flanged to reduce the number of parts needed for holding the bearings. Attached to the shaft is a pulley for the actuation of foot. This pulley has the same design as the pulleys at the motors (section II-B). A shoulder bolt is used as a stop for the foot to prevent it from rotating more than one rotation.

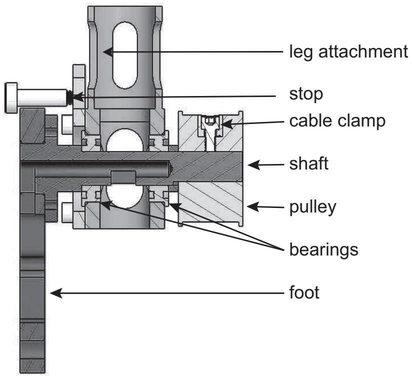

Fig. 15. Cross-section of the ankle

3) motorpulley design: Pulleys are used to connect the cables to the motors. These pulleys are made of two halves and clamp on to the shafts of the gearbox (figure

16). One of the halves has a flat spot to lock the D-shape shafts. There are two clamps on the pulley for clamping the cables. To reduce the force on the clamps the cables are wrapped a couple of times around to pulley. The pulley has a cut out so that it can be placed close to the gearbox to reduce the moment load on the bearings of the gearbox.

Fig. 16. Motor pulley

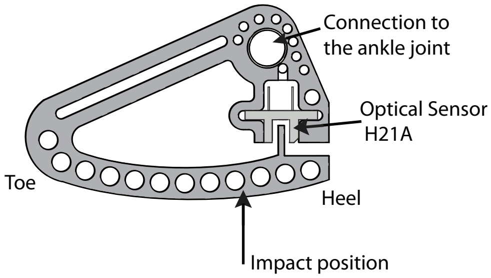

Fig. 17. Foot Design

4) torque estimation: Some tests has been done to use the compliance of the cables in order to estimate torque around the ankles. In testing the results were promising, it was possible to get a measurement of the force with an accuracy of $\pm$ 10 %. In normal use it isn't sure whether the information given by this estimation is accurate. A problem in using the cable stiffness in order to estimate the torque is that the backlash in the motor gearbox is of influence of the estimation. The the backlash in the motor gearbox is load dependent, and it is not sure whether this dependence changes over time. Since the cables used are very stiff in comparison to series actuation with a regular spring, a small error leads in the calibration leads to high errors in the output.

This since: $T = K_{cablestiffness} \times d\alpha$

in which $d\alpha$ is the angle difference between angle of the motor shaft and of the angle of the ankle shaft. A high cable stiffness means that a small error in $d\alpha$ leads to a bigger error. Since reading of the angle of the motor shaft is based on the encoder on the motor (before the gearbox), the gearbox can influence this calculation. The backlash in the motor gearbox is torque dependent, and it is at this point not sure what the amount of change is of this load dependent part of the backlash over longer time periods. This combined with the high stiffness makes it that the calculation of the torque applied using the cable stiffness is not yet trusted.

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