Development of WorkPartner-robot – design of actuating and motion control system

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ABSTRACT.

The paper deals with a new mobile robot platform with hybrid locomotion capability currently under construction. It is designed for a service robot, called WorkPartner, used mainly in outdoor environment when doing work interactively with humans. The estimated weight of the platform is about 160 kg and the pay-load about 60 kg. The actuation system is fully an electrical one and the power system a hybrid one with battery and a 3 kW combustion engine. The locomotion system includes legs with foot replaced by a wheel. It allows motion in three modes, with wheels only, with legs only, and hybrid locomotion with legs and wheels powered at the same time. With wheels, the machine is designed to obtain 7 km/hour speed on a hard ground. The purpose of the hybrid locomotion system is to provide a rough terrain capability and a wide speed range for the machine at the same time. The paper describes details concerning the design of the actuating and motion control system.

1. INTRODUCTION.

After the successful ten years research with the MECANT - machine (2) the Automation Technology Laboratory at HUT has started the project to construct a new generation walking machine which will be a prototype service robot for multi-tasking work. We call the robot WorkPartner, because the idea is to make a highly adaptive robot, which can carry different tools and work interactively with a human person by learning at the same time the details of the task. The platform, shown in Fig. 1, on which the robot will be built is called HYBTOR (Hybrid Tractor). It has four legs equipped with wheels and an active body joint. The weight is estimated to be about 160 kg and the pay-load about 60 kg. The actuation system is fully an electrical one and the power system a hybrid one with batteries and a 3 kW combustion engine. The locomotion system allows motion with wheels only, with legs only, or with legs and wheels powered at the same time. With wheels the machine can obtain ~7 km/hour speed on a hard ground. The purpose of the hybrid locomotion system is to provide a rough terrain capability and a wide speed range for the machine at the same time. The mechanical design
has been made in cooperation with Russian Rover Company Ltd. (St Petersburg) specialized on space robotics. The company also manufactures the platform. The electronics and software are designed and produced by the Intelligent Machines and Special Robotics Institute at HUT. The WorkPartner 1, the first generation prototype, will be ready at the end of 2000 and the third generation prototype WorkPartner 3 is estimated to be in use at the end of 2005.

Figure 1. The Hybtor platform for WorkPartner - robot

A leading idea is to make the design as modular as possible in mechanics, electronics and software. The platform mechanics is designed in such a way that all articulated movements can be realized by a similar linear actuator described in the following. The wheel movements are realized by motors assembled inside the wheel. All the electric motors are similar, 250 W EC-motors manufactured by Maxon. The linear actuator – the “muscle” of the robot – is designed to be a strong lightweight component. The electronics is designed by minimizing the number of cards and sensors of different type. The software is designed by using UML and modular object based approach.

2. **THE MAIN ACTUATOR**

The “muscles” the machine are identical linear actuators, shown in Figure 2. Each of them consisting a Maxon EC250W 48V electric motor, a gear taylor-made by Rover LTD and a ball screw from SKF (CCBR32x100). Inside the rod of the ball screw a bolt’s axial tension measuring foil strain gage has been mounted (Figure 2). With the force sensor, forces can be detected also when the actuator is not actively powered. The main performance values of the actuator are presented in Table 1.
### Table 1. Parameters of the actuator:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>2.4 kg</td>
</tr>
<tr>
<td>Length of stroke</td>
<td>100 mm</td>
</tr>
<tr>
<td>Gear ratio</td>
<td>6.084</td>
</tr>
<tr>
<td>Modulus of ball screw</td>
<td>4 mm/revolution</td>
</tr>
<tr>
<td>Max velocity (no load speed)</td>
<td>70.90 mm/s</td>
</tr>
<tr>
<td>Max force (continuous)</td>
<td>2500N (I=4.6A)</td>
</tr>
<tr>
<td>Self-locking force with brake</td>
<td>3042N (0.4 Nm brake)</td>
</tr>
</tbody>
</table>

![Image of actuator](image)

**Figure 2.** The main linear actuator used in WorkPartner -robot

### 2.1. Force tests of the actuator

The developed linear actuator with a force sensor has been tested using exterior force sensor (Kistler 9067 force sensor with a charge amplifier 5041b). The sensors were connected to the computer by DaqBook measurement card.

The theoretical force of the linear actuator is calculated as

\[
F = \text{current} \times \text{torque constant of motor} \times \text{gear ratio} \times \text{constant of ball screw}
\]

\[
F = I \times 71\text{Nm/A} \times 6.084 \times 1250(1/m) = 540 \text{ N/A} \times I
\]

According to Figure 3, where the corresponding measurements are shown, the force produced by the actuator is quite linear related to the current of the motor. Because of a static friction, the force calculated from the current is growing faster that the actual one. Same effect can be observed in reducing force, the actual force keep longer in higher level. The step-shaped force graph also derives from static friction. Comparing the mounted strain gage force sensor with the exterior one, forces observed are quite similar, only the set point of strain gage is little erroneous.
2.2. Velocity of the linear actuator

Velocity of the linear actuator depends on speed of the motor and gear reduction. In general, the actuator has to fulfill force and velocity requirements. Because of the both properties are depending each other only way to improve velocity or force is to grow power of the motor. Therefore, powerful EC motor with a large operating speed has been chosen. Maximal velocity of the actuator is approximately 70 mm/s as we see in the Table 1. In addition, the EC-motor has good heat dissipation due to motor winding putted in outer shell.

Theoretical velocity of the linear actuator:
\[ V = \text{voltage} \times \text{speed constant of motor} \times \text{gear ratio} \times \text{modulus of screw} \]
\[ V = \text{voltage} \times 135 \text{rpm/V} \times 6.084 \times 4 \text{ mm/revolution} \]

2.3. Advantage of the linear actuator with EC-motor

According to Table 2, the linear actuator of WorkPartner has better force and velocity characteristic than commercial linear actuators available at the moment in markets. That is because of the new powerful Maxon EC motor, which is very light, weighting only 1,2 kg, and has a large operating speed (6470-rpm).
### Table 2. Comparison of linear actuators.

<table>
<thead>
<tr>
<th></th>
<th>Max dyn.load</th>
<th>Linear speed</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>SKF CARR32x100x2</td>
<td>2500 N</td>
<td>18-10 mm/s</td>
<td>2.2 kg</td>
</tr>
<tr>
<td>SKF CARR40x100x4</td>
<td>2000 N</td>
<td>60-40 mm/s</td>
<td>5.8 kg</td>
</tr>
<tr>
<td>RACO T6G2-0113</td>
<td>2000 N</td>
<td>20 mm/s</td>
<td>3.5 kg</td>
</tr>
<tr>
<td>LINAK LA30.2S</td>
<td>2400 N</td>
<td>36 mm/s</td>
<td>? kg</td>
</tr>
<tr>
<td>HYBTOR</td>
<td>2500 N</td>
<td>70 mm/s</td>
<td>2.4 kg</td>
</tr>
</tbody>
</table>

3. **THE WHEELED LEG**

The test system of the robot, including two legs and the body joint is illustrated in Fig 4. One leg weights, including the wheel, about 21 kg. It is capable to produce about 70 kg continuous and 100 kg peak force in the driving position. The maximum stride length when walking is about 0.7 m.

The leg of grown-up human man weights little bit less than 20 kg and can produce about the same forces as Hybtors leg can. If we take the wheel and the motor away (8.5 kg) from the Hybtor's leg, it is comparable with human leg, also as to the step length.

![Figure 4. Side view of the machine](image)

The wheel has two functions, a rounded shape rubber wheel works as a foot in the walking mode and as a wheel in driving mode. The rubber wheel absorbs shocks generated in fast walking. With a gear reduction 84,2 the wheel reaches up angular velocity 462 °/s as we see in the table 3. This means that the vehicles maximum speed is approximately 7 km/h. Later, when improving speed of the machine EC250W motor can be replaced stronger 500W motor or the one stage gearbox can be rebuild into two stage gearbox.

Because of the commercial heavy rubber tire and the wheel disk (mass of the rubber tire and the wheel disk is 6.7 kg) the moments of inertia of the joints are quite high, although moment of inertia are calculated without rotors of the motors and tooth wheels (see table 3). High inertia of moments especially has negative effect in fast walking. Using the advanced lightweight wheel disk and the optimized rubber tire the mass of the wheel can be reduced to 4 kg. In the table 3 other parameters of the leg can be found.
Table 3. Parameters of the leg

<table>
<thead>
<tr>
<th>Joint</th>
<th>Angle $\alpha$ $[^\circ]$</th>
<th>Max. angular velocity $\omega$ $[^\circ]/s$</th>
<th>Max. torque $M$ [Nm]</th>
<th>Max. moment of inertia $J$ [kgm$^2$]</th>
<th>Links $l$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip (inclination)</td>
<td>$\pm 20$</td>
<td>28,4</td>
<td>358</td>
<td>3,44</td>
<td>138</td>
</tr>
<tr>
<td>Thigh (rotation)</td>
<td>0 - 70</td>
<td>48,9</td>
<td>220</td>
<td>5,76</td>
<td>500</td>
</tr>
<tr>
<td>Knee</td>
<td>0 – 140</td>
<td>90,4</td>
<td>112</td>
<td>1,52</td>
<td>400</td>
</tr>
<tr>
<td>Wheel</td>
<td>8</td>
<td>462</td>
<td>27,7</td>
<td>0,162</td>
<td>230 (radius)</td>
</tr>
</tbody>
</table>

The leg is controlled in different modes depending on the state of the robot and needs of controlling the body motion. The modes allow force, velocity and positional control of the joints. In addition, brakes in the motors are used actively to lock the joints when feasible. All these functions are taken care by the leg controller, which is commanded from the upper level of the overall control system. The design allows changes of control modes automatically so that the robot can change e.g. from velocity control to force control when stopping moving and starting working. More about the principles of leg control software in the following.

4. THE OVERALL CONTROL SYSTEM

The main function of the overall control system includes several new features if compared to classical walking machine functions. The hybrid locomotion system and automatic mode changes are features that have been studied only little so far.

The wheeled driving mode is like traditional wheeled vehicle, only additions are active balancing and attitude control and an active suspension. The walking mode is like any four-legged machine, only the foot is bigger than normally due the wheel. The hybrid locomotion mode it could be understood as walking without lifting the legs, but unloading and driving them in the transfer phase. The control system should be able to change these modes automatically, also so that one leg could be in one mode and another leg in other mode.

4.1. Hardware

The computer system is distributed around CAN-bus as illustrated in figure. Each leg has one controller based on Siemens 167 Micro-controller and PHYTEC 167-mini-MODULE. A manipulator that will be added later is considered as an optional leg. Other nodes, demanding more computing resources - like those taking care of motion and locomotion control, user interface or perception system devices - are based mainly on PC-104 card technology. Also additional computer power can be used, via wireless local area network, WLAN. The main computer is a 586 PC-104 board and is running on QNX operating system. The electronics include also servo controllers for the actuator motors and specially made amplifier cards for force sensors in legs and shoulder actuators.

All the hardware is modular and easy to maintain. In a fault situation the computer control system can be by-passed and the machine can be driven manually with an extra control box.
Figure 5. Overall schema of the on-board control system

4.2. Software

Software planning and designing has been started and is done with the CASE-tool PROSA using UML description. A systematic way to develop the software is considered very important in the project because of its scale and number of people included. The robot will also evolve through several generations, which causes special needs to modular design and documentation of the software.

The program code will be written with object-oriented methods and divided into logical parts and levels starting from the overall controlling part going down to basic controllers and limit switches.

The main principle of the control software is presented in figure 6. Because the machine can move in different modes, most of these objects have different modes, and sub-modes. This gives the code the basic modularity and also lots of challenges to make it functional.

The Operator Interface (OI) will in the first phase be more like a standard user interface, but in the later stages its role will be changed towards a high level multimedia interface through which the user can communicate with the robot like a working partner. Not shown in this basic diagram are the perception and manipulator modules, which are optional and will be joined later on.
One of the control ideas is to ask service from each \textit{LEG} and let the leg do most of the needed control algorithms by itself. Every leg is more or less an individual object containing the whole leg including the wheel, all the controllers, sensors and limit switches, the control software, and the communication between leg controller and main computer. The legs can not be totally independent agents because then they would have to communicate to each other and the only gait they could provide is simple wave gait. In our opinion there must be the overall control of the machine, in this case the main computer. In the \textit{Walking mode} the leg is only asked to go to the next step position or to move the body to a certain direction. The leg also can be forced to go to the support phase in the middle of the transfer phase. In the \textit{Driving mode} the leg is either stiff or sprung and the service demands are routed to the wheel.

\textit{Gait controller} controls the gating of the machine according to the stability, walking mode and other needed info. It also controls the leg movements in hybrid locomotion mode.

\textit{Body object} controls the attitude of the machine using the legs directly. In the driving mode it also calculates the body joint angle and the speeds of the wheels according to the operator commands.

The \textit{Additional calculation} part contains many functions or objects, which give vital information to the main part, locomotion controller. It includes, at least, Attitude Controller, Terrain Approximation, COG Calculation, Stability Calculations, Force Distribution Calculations, and more.

\textit{Locomotion controller} then gives orders, information or asks for service from all the other parts of the system. It chooses the right modes and commands the appropriate objects to gain the required movement.

5. **OBSERVATIONS AND CONCLUSIONS CONCERNING THE PROJECT**

At the present state the project is going toward the final assembly of the mechanics. Basic tests with the leg/wheel mechanics and its control system have been done. The have proved the mechanical design very satisfactory. The leg force/speed characteristics are good and power to weight ratio is high. After some problems with the Maxon new EC-motor and its
driving electronics also the “muscle” works now well. The next step is to make the tests with the entire Hybtor platform. As a parallel process writing the software for the higher levels has also been started. The core of the motion control software will be transported from MECANT software which is modified for four legged robot and hybrid locomotion mode. It is estimated that the basic mobility of the platform under computer control can be tested at the end of the current year 1999. After that the project will be splitted in three sub-projects, one developing further the mobility system, the second one working with the perception and navigation system and the third one developing the operator system which include advanced features. The perception system will use a stereo vision and laser hardware. The navigation system will include a gyro based dead-reckoning hardware. The basic problem to be studied is the simultaneous mapping and navigation in the close working environment. This will be later on enlarged to an interactive process with the operator who uses the control interface to command the robot.

At last but not least it should be mentioned that the project include also a separate art design project carried out by the University of Lapland in Rovaniemi. This project will design an appearance for the WorkPartner robot taking into account its purpose of utilization and close contacts with humans. The art design project will produce covers for the Hybtor platform and also consider aspects like motion details and noise.

REFERENCES


The research reported in this paper has been supported by TEKES under the contract no. 40262/99 and by the Academy of Finland by the contract no 40656.