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Hypermobile Robots

Grzegorz Granosik
Technical University of Lodz
Poland

1. Introduction

Hypermobile robots belong to the group of hyper-redundant articulated mobile robots. This group can be further divided based on two characteristic features: the way the forward motion of the robot is generated and the activity of its joints, as shown in Table 1.

Propulsion→ Joints↓	External propulsion elements: legs, wheels, tracks	Movement is generated by undulation
Active joints	**Hypermobile robots:** • Koryu-I and Koryu-II (Hirose, 1993) • Snake 2 (Klaassen and Paap, 1999) • Soryu (Takayama and Hirose, 2000) • Millibot Train (Brown et al., 2002) • Moira (Osuka & Kitajima, 2003) • Pipeline Explorer (Schempf et al., 2003) • Omnis family (Granosik et al., 2005) • MAKRO *plus* (Streich & Adria, 2004) • KOHGA (Kamegawa et al., 2004) • JL-I (Zhang et al., 2006) • Wheeeler (Pytasz & Granosik, 2006)	**Snake-like robots:** • Active Cord Mechanism whole family of robots (Hirose, 1993) • Slim Slime Robot (Ohno & Hirose, 2000) • Snake robots by Dr. Gavin Miller (snakerobots.com) • Perambulator-II (Ye et al., 2007)
Passive joints	**Active wheels – passive joints robots:** • Genbu 3 (Kimura & Hirose, 2002)	

Table 1. Articulated mobile robots

Articulated robots can also be divided in other way, as suggested by Robinson and Davies (1999), into three groups: discrete, serpentine and continuum. Most robots are discrete mechanisms constructed from series of rigid links interconnected by discrete joints. In case of robotic manipulators joints are usually one degree of freedom (DOF) but in case of articulated mobile robots we can find 2 and 3 DOF joints more often. Multi degree of freedom joints create naturally spatial devices, which can bend in any direction.
Serpentine robots also utilize discrete joints but combine very short rigid links with a large density of joints. This creates highly mobile mechanisms producing smooth curves, similar to snake. And therefore representatives of this group of robots are also called snake-like

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robots, as shown in Fig. 1. Some of the hypermobile robots feature very short links relative to the cross section size and also belong to this group.

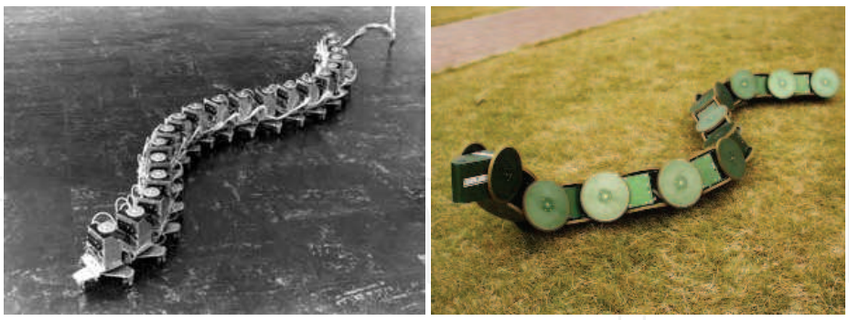


Fig. 1. Active Cord Mechanism (left) reproduced from (Hirose, 1993), ACM-R3 reproduced from (Mori & Hirose, 2002)

Continuum robots do not contain rigid links and identifiable rotational joints. Instead the structures bend continuously along their length via elastic deformation and produce motion through the generation of smooth curves, similar to the tentacles. The good example of continuum mobile robots is Slim Slime Robot (see Fig. 2).



Fig. 2. Slim Slime Robot reproduced from (Ohno & Hirose, 2000)

In the next part of this paper we present a few major projects of hypermobile robots from around the world, focusing on comparison of design concepts, main features, performance, teleoperation or automated operation techniques. Finally, we present our own hypermobile robot Wheeeler showing design concept, model, simulation results, construction and tests of prototype. In conclusion we summarize this digest with a table showing basic properties of presented robots. We also show advantages and disadvantages of our design and future plans. We hope to show some general ideas on designing, constructing and control of such complex devices as hypermobile robots with many redundant degrees of freedom.

2. History of hypermobile robots

One of the scenarios where hypermobile robots could play the main role is search and rescue. The intensified work in this field was related to the large catastrophes happened in different countries: Kobe earthquake, terrorist attacks on World Trade Center in New York and bomb attacks on trains in London and Madrid. In this application robots are intended to slither into the debris and gather visual information about possible victims. Therefore, it is expected that robot fits small openings, can travel in the rummage of structured

environment and overcome obstacles. The other important application for hypermobile robots are inspection tasks in sewage systems, gas pipes or venting systems.
The first practical realization of a hypermobile robot, called Koryu or KR-I, was introduced by Hirose and Morishima (1990) and later improved with version KR-II (Hirose et al., 1991), as shown in Fig. 3. KR-II was developed with premise that it will be applied as a mobile robot for atomic reactor. It was also considered to be used as a substitution of fireman in rescuing activity: patrolling, gas detection, inspection and to rescue a person. This first hypermobile robot was large and heavy, weighing in at 350 kg. The robot comprised of multiple vertical cylindrical segments on powered wheels (tracks in KR-I) that gave the mechanism a train-like appearance. Vertical joint actuators allow a segment to lift its neighbors up, in order to negotiate steps or span gaps. Each segment of KR-II is equipped with single wheel, arranged so that the unit with wheel on the right side will come after a unit with the wheel on the left side. This single wheel design may seem unbalanced at the first glance but its stability is secured as the segments are linked. Especially, if the vehicle have the zigzag configuration. Moreover, this single wheel design has other advantages:

- as each segment is connected to the body by 2DOF joint it may be seen as having sliding active suspension,
- the adaptability to the steep inclination during traversing can be realized by shifting all wheels on one side up or down in vertical direction,
- in addition, this design doesn't require the differential mechanism of the double wheel structure to permit different speed rotation on curves.



Fig. 3. The Koryu-I (KR-I) robot on the left and KR-II on the right (reproduced from http://www-robot.mes.titech.ac.jp)

These robots inherited all capabilities of earlier developed snake-like robots:

- They can go on irregular terrain with sharp rises and falls and travel a path that winds tightly,
- They can cross over crevasses by holding its body length rigid to act as a bridge,
- In marshy and sandy terrain, it can move by distributing force along its entire body length.

Additional active crawlers or wheels mounted on each segment give further advantages:

- High speed motion – direct propulsion is more effective then undulation,
- High load capacity – simple driving system gives large weight of load to its own weight ratio,
- Good portability by its unitized structure,
- High reliability, because it is made redundant – broken segments can be easily replaced and special segments could be added depending on mission,

- Versatility of the body motion – Koryu can be used not only for "locomotion", but also for "manipulation" – as claim authors (Hirose & Morishima, 1993).

For motion control of the robot with several wheels touching ground the force sensors to detect reaction force were indispensable. To solve the problem, special construction of optical based force sensing was introduced. Such sensors were mounted in both vertical and horizontal axes to control robot among obstacles and on uneven terrain.

More recently, Klaassen and Paap (1999) at the German National Research Center for Information Technology (GMD) developed the Snake2 vehicle, which contains six active segments and a head, as shown in Fig. 4. Each round segment has an array of 12 electrically driven wheels evenly spaced around its periphery. These wheels provide propulsion regardless of the vehicle's roll angle. Segments are interconnected by universal joints actuated by three additional electric motors through strings. Snake2 is an example of a robot that is inspired by the physiological structure of snakes where wheels replace tiny scales observed on the bodies of some real snakes. Snake2 is equipped with six infrared distance sensors, three torque sensors, one tilt sensor, two angle sensors in every segment, and a video camera in the head segment. Snake2 was specifically designed for the inspection of sewage pipes. With segments measuring 18cm in diameter and 13.5cm length Snake2 belongs to the serpentine group.



Fig. 4. Snake2 developed at the GMD

This robot was a successor of the GMD-Snake, typical continuum spatial robot built in a very elastic way to allow flexible bending of the parts (Worst & Linnemann, 1996). However, Authors observed an uncontrolled torsion effect which occurred when the snake lifted some of its parts (to climb on a step). This disadvantage forced them to construct the next generation in a more rigid way using universal joints but leaving rope-based driving system. GMD snakes were the first articulated robots employing CAN bus communication in the distributed control system.

Another hypermobile robot designed for sewer inspection was developed by Scholl et al. (2000) at the Forschungszentrum Informatik (FZI) in Germany. Its segments use only two wheels but the actuated 3-DOF joints allow full control over each segment's spatial orientation. The robot is able to negotiate tight 90° angled pipes and climb over 35 cm high obstacles. One segment and its joint are about 20 cm long each. The sensor suite of this robot is similar to that of Snake2. The development of sewer inspection robots was continued in the joint project MAKRO *plus* (Streich & Adria, 2004).

MAKRO *plus*, is an autonomous service robot that can be used for a whole range of specific duties within a canalization system. Robot has symmetrical construction with head segments on both ends. These segments contain camera, structured light source and ultrasound sensor. Four-level hierarchical control system is proposed to autonomously

drive robot inside sewage pipes. The robot's mission is specified by human operator who determines entry and recovery points and downloads map of all pipes and manholes in the inspection area. Then the planning algorithm generates the sequence of actions, which are executed by action controller. In case of obstacle detection, blockage or malfunction, planner automatically finds new set of actions. Robot can be equipped in specialized modules. A chemistry module measures pH levels, conductivity, O_2 and temperature of waste water with the help of a sample probe. When required, samples can be retrieved by the robot for further analysis in a laboratory. A navigation module which can record speed and three fiber optic gyroscopes measure the gradient and direction of the pipes in a canalization system. This helps to support the success of the mission and it is also provides a useful and accurate update for the land registry records, as informs INSPECTOR SYSTEMS Rainer Hitzel GmbH.



Fig. 5. MAKRO *plus* robot for sewer inspection (reproduced from Streich & Adria, 2004)

While wheeled serpentine robots can work well in smooth-walled pipes, more rugged terrain requires tracked propulsion. To this effect Takayama and Hirose (2000) developed the Souryu-I crawler, which consists of three segments, as shown in Fig. 6.



Fig. 6. Souryu from Hirose Lab (reproduced from http://www-robot.mes.titech.ac.jp)

Each segment is driven by a pair of tracks, which, in turn, are all powered simultaneously by a single motor, located in the center segment. Torque is provided to the two distal segments through a rotary shaft and universal joints. Each distal segment is connected to the center segment by a special 2-DOF joint mechanism, which is actuated by two lead screws driven by two electric motors. The robot can move forward and backward, and it can change the orientation of the two distal segments in yaw and pitch symmetrically to the center segment. Coordinated rotations of these joints can generate roll over motion of the robot. One interesting feature is the ability of this robot to adapt to irregular terrain because of the elasticity of its joints. This elasticity is provided by springs and cannot be actively controlled. The newest incarnation – Souryu-II – is designed to separate three bodies easily

so as to make it portable and to make it possible to add segments with special functions. Robot is equipped with camera and batteries, and can be remotely controlled.
A different concept using unpowered joints was introduced by Kimura and Hirose (2002) at the Tokyo Institute of Technology. That robot, called Genbu (see Fig. 7), is probably the only serpentine robot with unpowered joints. The stability of the robot and its high mobility on rough terrain are preserved by large-diameter wheels (220 mm). The control system employs position and torque feedback sensors for the passive but rigid joints. Springs are used to protect the electric motors from impact, although the stiffness of the springs cannot be controlled during operation. Robot was intended mainly for two applications: as a fire-fighting robot to pull a fire hose or as a planetary rover.



Fig. 7. Robot Genbu representing group of active wheels – passive joints robots

Another robot incorporating a combination of passive and active joints as well as independently driven and coupled segments is KOHGA developed by Kamegawa et al. (2004) and shown in Fig. 8. Robot comprises 8 segments of different structure and function: two distal segments have CCD cameras mounted but have no propulsion means, the second units have the right and left crawlers which are driven co-accessibly, the other segments also have the right and left crawlers but independently driven. There is also a variety of joints implemented in this design:

- Two 2DOF joints driven by simple RC servos to control position of heads with cameras,
- Two 2DOF joints with powerful DC motors and linkages to rise two segments on either end, this improves the capability of climbing over obstacles,
- Three 3DOF passive joints interconnecting main driving units, their function is to adjust robot's shape to the environment and efficiently transmit crawler force, they are passive for light weight and simplicity.

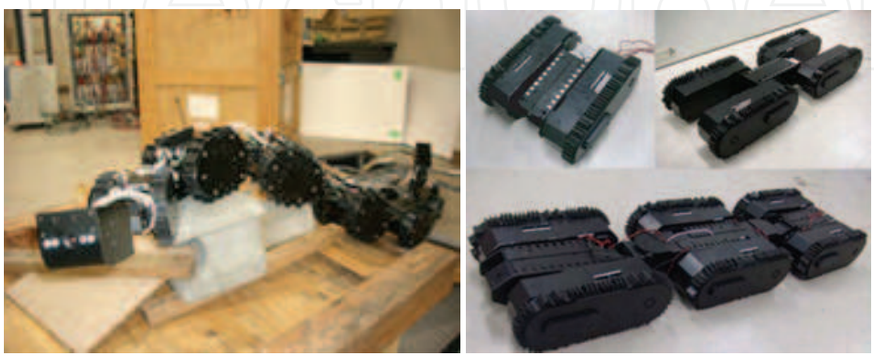


Fig. 8. Robot KOHGA and KOHGA 2 (in a few configurations) from Matsuno Lab. at the University of Electro-Communications

This robot implements a smart design feature: besides a camera in the front segment, there is a second camera in the tail section that can be pointed forward, in the way a scorpion points its tail forward and over-head. This "tail-view" greatly helps teleoperating the robot. Operator is using SONY gamepad as user input and monitor with specially organized video outputs. Authors proposed also algorithm (based on robot kinematics only) to calculate speed of tracks and rotation of joints to realize follow-the-leader control of robot.

KOHGA with its passive joints has an important problem that obstacles can be caught to the joints and then the robot is stuck. To solve this problem, the new reconfigurable version of KOHGA 2 was developed (Miyanaka et al. 2007). The unit structure consists of the crawler-arm-units, the joint-units, the terminal-units and the connecting parts. It can work as a self-contained module or can be connected with other units creating multi-segmented vehicle. Moreover, it can take various forms by the swing motion of the crawler-arms, and avoid various stuck conditions. These crawler-arms can be mounted in two ways: the rotational axes of right and left crawler-arms are alternately attached to the vehicle (called the non-coaxial type), or these axes are attached to the same end of the vehicle (called the coaxial type). Authors have considered several robot configurations, in different stuck-prone conditions, in both high- and low-ceiling environments. They concluded that (1) the ability of the stuck avoidance declines if the number of the connected vehicles is small because the performance of vertical step climbing falls off and (2) that the coaxial type robot is more effective to the stuck avoidance than the non-coaxial type robot.

The concept of joining several small robots into a train to overcome larger obstacles was used by researchers from Carnegie Mellon University in their Millibot Train (Brown et al., 2002). This robot consists of seven electrically driven, very compact segments. The diameter of the track sprockets is larger than the height of each segment, which allows the robot to drive upside-down. Segments are connected by couplers for active connection and disconnection, but the joints have only one DOF. Each joint is actuated by an electric motor with a high-ratio harmonic gear and slip clutch. It provides sufficient torque to lift up the three front segments. The robot has been demonstrated to climb up a regular staircase and even higher steps. However, with only one DOF in each joint the vehicle is kinematically limited.

A serpentine robot that uses tracks for propulsion and pneumatics for joint actuation is MOIRA shown in Fig. 9 (Osuka & Kitajima, 2003). MOIRA comprises four segments, and



Fig. 9. Robot Moira from Osuka Lab.

each segment has two longitudinal tracks on each of its four sides, for a total of eight tracks per segment. All tracks are driven from a single motor through the system of 4 bevel and 4 spiral gears and therefore they move in the same direction. With tracks on each side robot is

insensitive for rollovers and with additionally cone shaped distal segments robot can dig into the debris with obstacles touching it from all sides. The 2-DOF joints between segments are actuated by pneumatic cylinders. Although with pneumatic cylinders MOIRA can lift up its segments high enough to overcome obstacles, it can also decrease stiffness of actuators to nicely conform to the ground, but we think that with very long joints this design is prone to getting stuck on some narrow obstacles. Robot is controlled from the specially designed control box containing 3 joysticks and several switches. There is also view from nose CCD camera transmitted via USB.

The newest construction from NREC (National Robotics Engineering Center) is Pipeline Explorer – robot designed and built for inspection of live gas pipelines (Schempf et al., 2003). This robot, shown in Fig. 10, has a symmetric architecture. A seven-element articulated body design houses a mirror-image arrangement of locomotor (camera) modules, battery carrying modules, and support modules, with a computing and electronics module in the middle. The robot's computer and electronics are protected in purged and pressurized housings. Segments are connected with articulated joints: the locomotor modules are connected to their neighbors with pitch-roll joints, while the others – via pitch-only joints. These specially designed joints allow orientation of the robot within the pipe, in any direction needed.

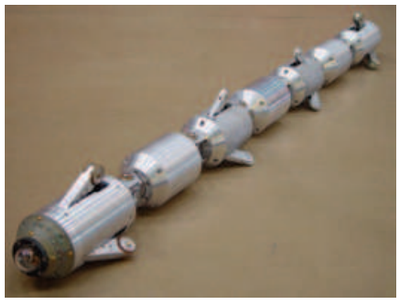


Fig. 10. Pipeline Explorer from NREC (reproduced from http://www.rec.ri.cmu.edu/projects/explorer)

The locomotor module houses a mini fish-eye camera, along with its lens and lighting elements. The camera has a 190-degree field of view and provides high-resolution color images of the pipe's interior. The locomotor module also houses dual drive actuators designed to allow for the deployment and retraction of three legs equipped with custom-molded driving wheels. The robot can sustain speeds of up to four inches per second. It is fully untethered (battery-powered, wirelessly controlled) and can be used in explosive underground natural gas distribution pipelines. Construction of robot naturally limits its application to pipes of certain diameters.

From 2002 to 2005 researchers from the Mobile Robotics Lab at the University of Michigan introduced the whole family of hypermobile robots called Omnis, shown in Fig. 11. In the OmniPede, the first one, they introduced three innovative functional elements: (1) propulsion elements (here: legs) evenly located around the perimeter of each segment; (2) pneumatic power for joint actuation; and (3) a single so called "drive shaft spine" that transfers mechanical power to all segments from a single drive motor (Long et al., 2002). From the study of the OmniPede, and from the observed shortcomings of this legged propulsion prototype, they derived important insights about the design of serpentine robots. These insights led to the development of the far more practical "OmniTread"

serpentine robot (Granosik et al., 2005). The OmniTread design offers two fundamentally important advantages over its predecessor and, in fact, over all other serpentine robots described in the scientific literature to date. These features are: maximal coverage of all sides of all segments with propulsion elements, joint actuation with pneumatic bellows. We believe that the bellows-based joint actuators used in OmniTread have a substantial advantage over a cylinder-based design, as discussed in Granosik & Borenstein (2005).
This robot passed extended tests at SouthWest Research Institute in Texas showing excellent performance on the send and rock testbeds as well as in the underbrush. It can climb obstacles 2.5 times higher then itself and span trenches almost half of own length. The latest version of the OmniTread is called OT-4 as it can fit through a hole 4 inches (10 cm) in diameter (Borenstein et al., 2006). The OT-4 is even more versatile then its predecessors, with onboard power sources (both electric and pneumatic) it can operate up to one hour, with wireless communication is completely tetherless, with clutches can precisely control power consumption, and with additional flipper-tracks can easily overcome the knife-edge hole obstacle and climb almost 5 times its own height. The detailed information on performance of all members of the Omnis family can be found in (Granosik et al., 2007).

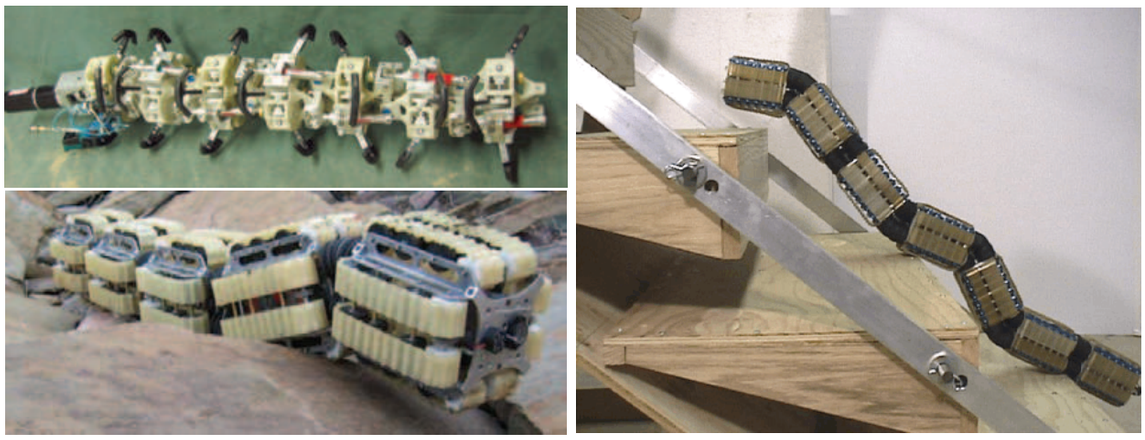


Fig. 11. The Omnis family of hypermobile robots from University of Michigan: OmniPede (upper left), OmniTread (lower left), OT-4 (right)

Another example of reconfigurable hypermobile robot was developed by Zhang et al. (2006). The JL-I system, shown in Fig. 12, consists of three identical modules; actually each module is an entire robotic system that can perform distributed activities. Vehicles have a form of crawlers with skid-steering ability. To achieve highly adaptive locomotion capabilities, the robot's serial and parallel mechanisms form an active joint, enabling it to change its shape in three dimensions. A docking mechanism enables adjacent modules to connect or disconnect flexibly and automatically. This mechanical structure and the control system are intended to ensure optimal traction for assembled robot. Each module is an autonomous mobile robot capable of performing basic tasks such as search and navigation. In order to achieve all these functions, the control system of the robot is based on distributed architecture with wireless connection to the base station. This flexible system with several identical modules which can work separately or simultaneously when assembled, required hierarchical software, based on the multi-agent behavior-based concept. Robot showed ability to climb steps, span gaps and recover from any rollover situation.

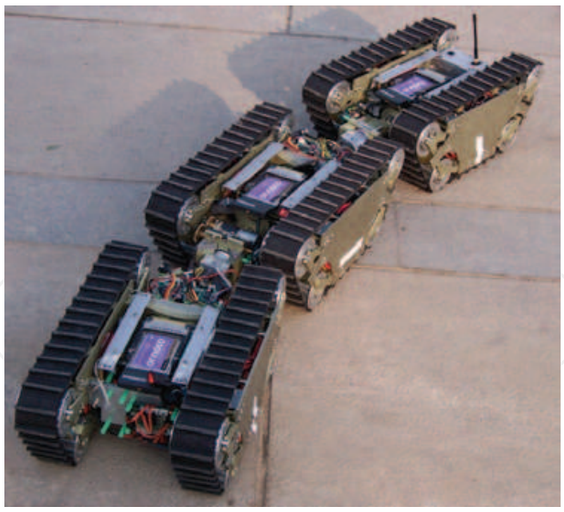


Fig. 12. Reconfigurable robot JL-I developed by Zhang et al. (2006)

3. Wheeeler project

Our project is focused on precise modeling and simulation of hypermobile robot in a testing environment, and eventually building it in as simple as possible way to verify a high level control concept. As we observed from the literature review, most of the hypermobile robots presented to date lack the autonomy or intuitive teleoperation, or this autonomy is limited to very specific environment of operation. Although, every robot has some control system but in most cases they employ multi DOF joysticks (Osuka & Kitajima, 2003) or sophisticated user interfaces (Baker & Borenstein, 2006), or require more then one operator. Our goal is to simplify teleoperation of these robots and increase their applicability. We consider articulated mobile robot propelled on wheels and therefore called – Wheeeler. We start with precise modeling of Wheeeler and designing the most intuitive user interface to control it. Then we show some mechanical details of suspension system and proof-of-concept prototype containing 3 identical segments built with many off-the-shelf components used in RC models technology.

3.1 Modeling and simulation

In this stage of a project we have used Webots PRO simulation software to model robot and working environment (Michel, 2004). Applying masses, inertias, friction coefficients and damping made model and simulation very realistic (see Fig. 13). Webots relies on ODE (Open Dynamics Engine) to perform accurate physics simulation and uses OpenGL graphics.

We assumed that robot will contain 7 identical segments interconnected by 2DOF joints allowing pitch and yaw rotations. Each segment has its own drive and suite of sensors including: 4 distance sensors facing up, down, left and right; encoder on main motor, 3 axis accelerometer and single axes gyro. We also assumed position feedback from joints and vision feedback from two cameras mounted on both ends of robot. With these two cameras robot will have advantages similar to Kohga robot providing operator with view from the nose camera and perspective view from behind and above the robot when tail of Wheeler is lifted in scorpion-like manner.

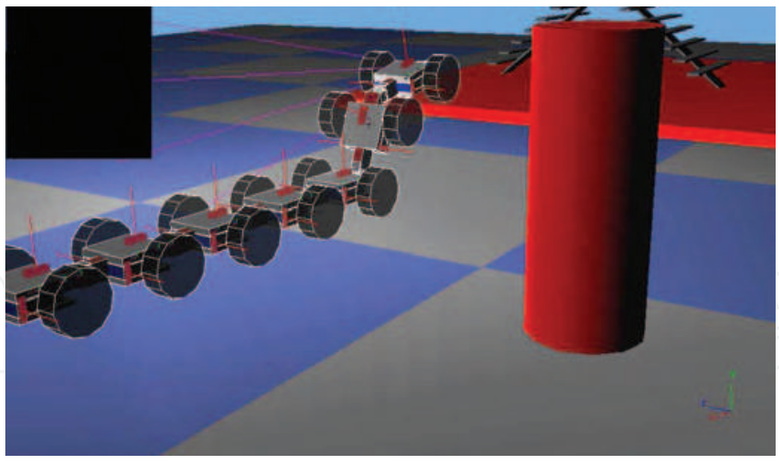


Fig. 13. Model of Wheeeler in Webots PRO simulator (Pytasz & Granosik, 2006)

In simulation environment we have access to information from all sensors. This data is processed by robot controller and streamed to the client-operator. CORBA framework has been used as communication layer. The choice was made because of its portability and flexibility and detailed explanation can be found in (Pytasz & Granosik 2007). With robot development and sensory suite extension the larger amount of data had to be transferred over network, including:

- control commands to robot,
- sensor data from robot,
- video streaming.

The selected mechanism allows for easy extension of communication features, decreasing probability of programming errors to occur. The same data structures and transport mechanisms as used in simulation will be verified in real robot.

Inter-segment joints working in vertical direction have a range of movement close to ±90, in horizontal it is a little over ±45. These ranges combined with short segments and zigzag posture of robot (e.g. as shown in Fig. 14) can compensate for lack of all side tracks (known from Moira or OmniTread). When rotation of upper wheels is opposite to the lower wheels robot is able to enter pipes, shafts, or low ceiling environments.



Fig. 14. Zigzag configuration of Wheeeler for working in pipes, shafts and low ceiling environments.

3.2 Mechanical concept

Designing Wheeeler we tried to take the best features of other hypermobile robots but we have also borne in mind that mechanical construction has to be simple. Impressed with behavior of Genbu – even with passive joints this wheeled robot can evade stuck situations, and envisaging easy method of driving two wheels on the common axel, we decided to use light-weight plastic wheels known from Monster Truck models (see Fig. 15). With big wheels, larger then segment's interior robot can easily ride upside down. The driving module uses single RC servo motor and bevel gear to transmit rotation directly to both wheels. We decided not to use differential mechanism to reduce weight and simplify transmission system. Moreover, for off-road vehicles it is much better to have the same speed and torque on both wheels to ensure grip on rocks or send, even though skidding will appear on the curves.

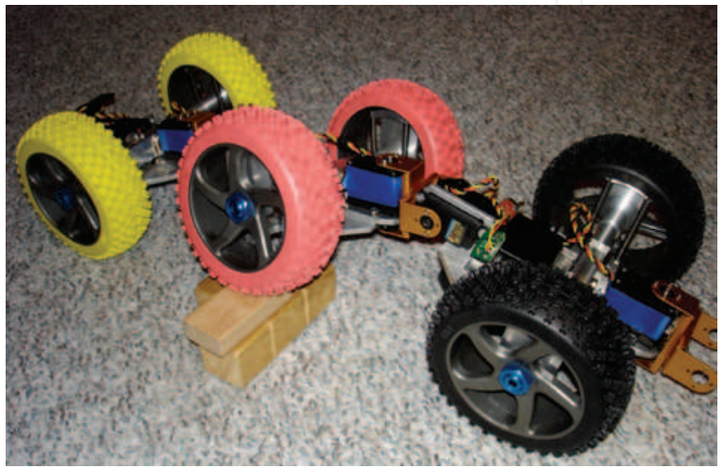


Fig. 15. Proof-of-concept prototype of Wheeeler – 3 segments (out of planned 7 segments) connected with 2 DOF joints

Hypermobile robots should conform to the terrain compliantly, so that as many driving segments as possible are in contact with the ground at all times to provide effective propulsion. Based on the literature review in the previous section and as shown in Table 4 there are, in general, three methods of adapting of articulated mobile robots to the rugged terrain. They are: active control of joints of the robot, passive joints and naturally compliant joints. The first method requires exact sensing of contact forces between propulsion means and the ground. Based on these measurements in each segment, control algorithm has to adapt joint position accordingly.

In case of robot Koryu the impedance control is proposed (Hirose & Morisima, 1993). It was shown that based on force sensing in both vertical and horizontal direction robot can follow the curvature of the ground and surmount higher, vertical obstacles.

For motion control of robot Makro: like branching into pipes, overcoming obstacles and driving at the bottom of the sewer, combination of 2D inclinometers (or 2 axes accelerometers) with joint angles sensing was proposed.

Active connection mechanism of Souryu introduces special elasticity. Rolling deformation is generated by the vehicle's own dead weight and does not interfere with proper operation of other DOF in joint thanks to combination of soft and hard springs. This elasticity also absorbs impacts. Pitch and yaw are also secured from impacts by additional springs.

In the robot Kohga full 3 DOF passive joints are used in the middle part of the robot – 4 central segments are interconnected by combination of freely rotating universal joint and

additional roll joint. This design allows the robot to adjust its shape corresponding to irregular surfaces, so that the driving force can be transmitted to the ground more effectively. The units, which are connected with passive joint, are controlled by driving the right and left crawlers independently instead of manipulating the joint.
Pneumatically driven joints of Moira and Omnis robots employ natural compliance of pneumatic springs. The advantage of using pneumatic springs instead of earlier mentioned solutions is possibility of controlling their stiffness actively. Regulating the level of pressures in chambers of the cylinders (driving Moira's joints) or in each of 4 bellows constituting Integrated Joint Actuator of OmniTread (or OT-4) changes spatial compliance of this joint. Therefore, theses robots can nicely conform to rock beds when joints go limp and a second later they can span gaps after pumping pressure up. Of course, the drawback of this solution is need of additional (pneumatic) source of power – increasing weight and noise.
We decided to combine active and stiff joints with passive suspension system in each segment and soft tires. Driving module (described earlier) is mounted in the base of the segment of Wheeeler rotationally in such a way, that it can rotate ±10° over longitudinal axis of the robot. This angle is measured with rotary potentiometer. Axis of wheels is supported by two ball-bearings in the funnel, which at ends is connected with the body of segment using 4 springs (Granosik et al., 2008).
We are very pleased with the behavior of Wheeeler's passive suspension, which helps to travel in an uneven terrain, as shown in Fig. 15, preserving continuous contact with ground for all wheels of the robot. Even for obstacles as high as half of wheel's diameter, springs allow each segment to conform to the ground and provide good grip for all tires.
In Fig. 16 we can see the behavior of springs depending on the position of wheel with respect to the floating platform. If wheel is lifted up by an obstacle springs extend as shown on the left part of Fig. 16, while springs on the wheel which is lower are compressed (right part).

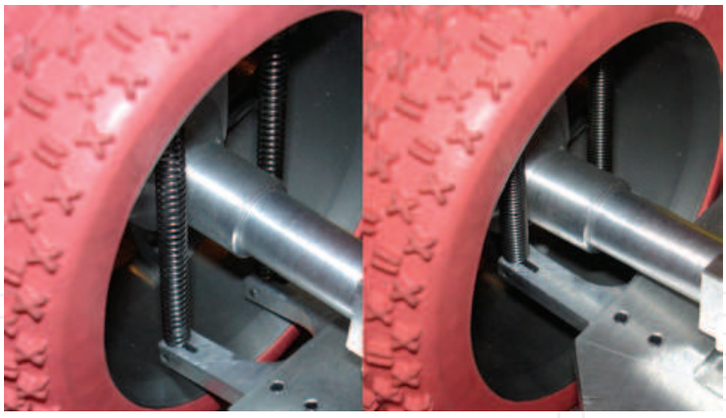


Fig. 16. Close view of springs in passive suspension of Wheeeler during riding over obstacle

3.3 Electronics

In order to control all the sensors envisioned in Wheeeler and in order to simply mechanical fit into the segment we have designed and built specialized controller based on the AT90CAN128 (Atmel), as shown in Fig. 17. We have chosen this processor for the fast AVR structure and relatively high processing power, as for 8-bit controllers. Additionally, in-system programming from Atmel offers reprogramming of each processor of the system directly through CAN bus. This will simplify development procedure of the robot's lowest level software. Local controllers are augmented with all necessary peripherials: 3-axis

accelerometers LIS3LV02DL (STMicroelectronics), single axis gyroscope ADIS16100 (Analog Devices), quadrature counters LS7366R (LSI/CSI) and IR distance sensors GP2D120 (Sharp). Functionality of controller can be further extended through serial communication interfaces: CAN, SPI, I2C and RS232. CAN bus is used as a main communication means for data acquisition and robot control.

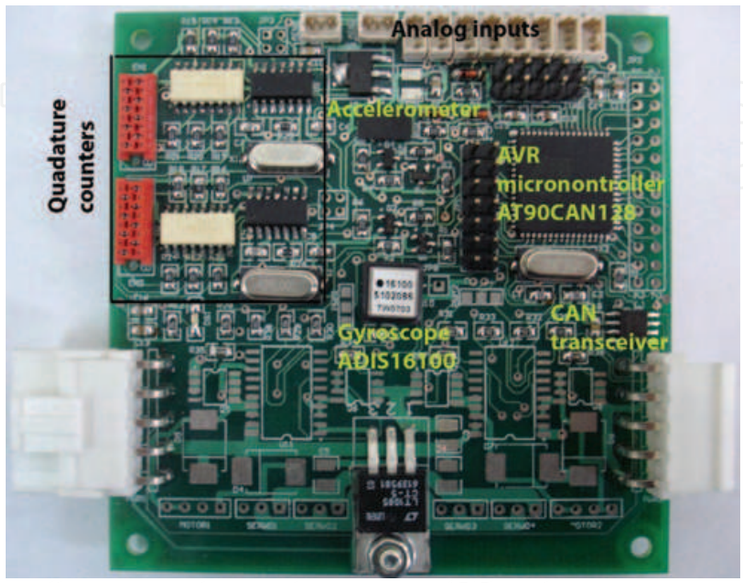


Fig. 17. Local controller mounted on each segment of Wheeeler

3.4 Controller

Local controllers are daisy-chained along robot's body and connected to the main controller realized on PC104 computer, as shown in Fig. 18. This main controller gathers data from robot and forwards to operators station via wireless link. It will also be used to transfer video signal. In the opposite direction, control orders comes from operator, they are being analyzed in main controller and distributed to local ones. We are planning that main controller will be also responsible for basic autonomous behavior of Wheeeler.

At first, basic teleoperation with only a visual feedback was introduced. Communication was unidirectional, allowing client (operator) send one of the following instructions:

- new angular velocity of the axle of specified segment,
- new position of the horizontal or vertical joint of a segment,
- stop all segments.

This form of control would be very inconvenient in a real application; therefore a simple propagation algorithm for angular position of joints was introduced. This algorithm is usually referred as follow the leader approach and is most often used to control serpentine and snake-like robots (Choset & Henning, 1999). However, this method requires very strong assumption that we know exact value of robot's speed with reference to the ground. Unfortunately, in most cases where hypermobile robots are intended to operate this condition is not fulfilled due to slippage, skidding on rocks or hitting obstacles. To improve operation of hypermobile robot among obstacles we are combining accelerometers' readings with potential field method based on the measurements of distances from each segment to the nearest obstacle. Using accelerometers we can detect wheel slippage and correct velocity accordingly. Using IR sensors we can check surroundings of the robot in four directions: up, down, left and right, and correct robot's trajectory according to these measurements.

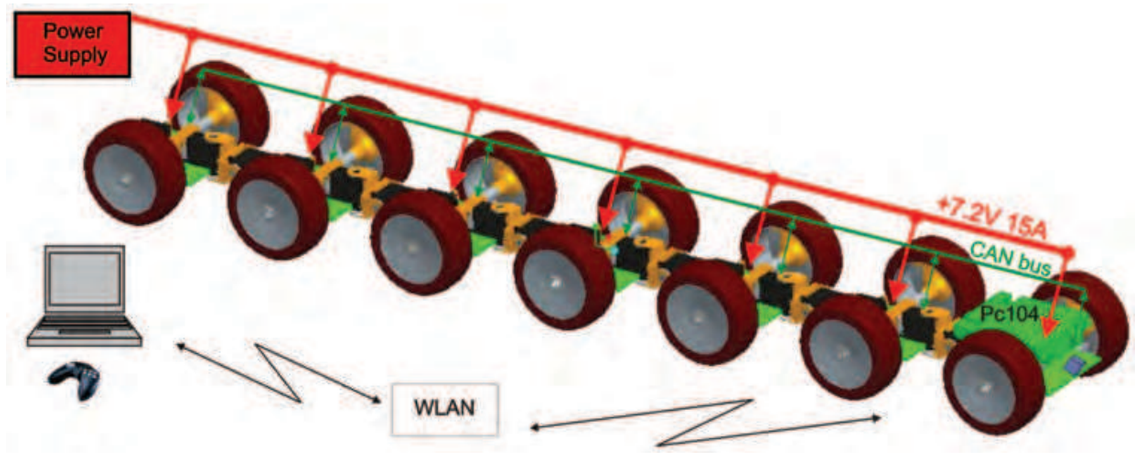


Fig. 18. Wheeler control structure

3.5 Tests

After building the proof-of-concept version of Wheeeler, consisting of 3 segments, we have made some preliminary tests to verify robot's behaviour, power consumption and performance. Results are presented in the following tables. Table 2 compares speed of the robot on the flat terrain (carpet) and supply current measured for three levels of supply voltage. Table 3 shows the current consumption during driving on the inclined steel flat surface (measurement for two inclinations and three voltage levels).

Supply voltage [V]	Speed of robot [cm/s]	Starting current [A]	Nominal current [A]
5	32.2	1.7	0.7
6	40.0	1.7	0.7
7	46.0	2.3	0.9

Table 2. Performance of 3 segment Wheeeler on flat terrain

Inclination [deg]	Supply voltage [V]	Starting current [A] Going up (down)	Nominal current [A] Going up (down)
16.2	5	2.6 (1.5)	1.4 (0.3)
	6	2.7 (1.6)	1.5 (0.3)
	7	2.8 (1.6)	1.7 (0.5)
21.3	5	2.6	2.0 (0.2)
	6	2.7	2.0 (0.3)
	7	2.8	2.0 (0.4)

Table 3. Power consumption of 3 segment Wheeeler on inclined surface

4. Conclusion

We have made an extended literature review in order to analyze methodologies used in designing and building hypermobile robots. We have also included our own experience in this field coming from Omnis project and recent Wheeeler development. The most important information of each hypermobile robot is summarized in Table 4.

Feature \ Robot	KR-II	Makro	Souryu	Kohga	Moira	OmniTread	OT-4	JL-I	Wheeeler
Number of segments	7	5	3	8	4	5	7	3	3 (7)
Length [cm]	330	160	116	205	143	127	94	105	55.5 (129)
Height [cm]	108	18	13.5	13.5	15	18.6	8.2	15	11.5
Width [cm]	46	20.3	17.5	18	15	18.6	8.2	25	21
Weight [kg]	320	30	10.2	18	18	13.6	4	21	2.7 (7)
Joints	2DOF, active electric	3DOF active electric	3DOF active electric	2DOF active electric, 3DOF passive	2DOF active pneumatic	2DOF active pneumatic	2DOF active pneumatic	3DOF active electric	2DOF active electric
Propulsion	wheels	wheels	treads	treads	treads	treads	treads	treads	wheels
No of propulsion means per unit	1	2	2	2	8	8	8	2	2
Speed [cm/s]	50	60	NA	5	20	10	15	18	40
Adapting to rugged terrain	Active control of joint	Active control of joint	Passivity in joint	Passive joints	Natural compliance	Natural compliance	Natural compliance	NA	Spring suspension
Max slope to travel [deg]	38	27	NA	30	34	30	40	40	21
Types of operation	Remote control	Remote control, some autonomy	Remote control,	Remote control, gamepad CAC	Remote control	Remote control, 2 gamepads	Remote control, 3 gamepads	NA	Remote control, gamepad CAC
Max height of obstacle [cm]	38	35	42	15	38	46	40	28	12
% of robot height	35	194	300	11	253	247	488	187	104
Rollover sensitivity	One side only	One side only	Upside down	Upside down	Four sides, insensitive	Four sides, insensitive	Four sides, insensitive	Upside down	Upside down
Low ceiling operation	Very limited	Limited	Limited	Limited	Unlimited	Unlimited	Unlimited	Limited/ possible	Limited/ possible

Table 4. Basic properties of hypermobile robots, CAC – computer aided control, NA – information not available

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