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Hypermobile Robots – the Survey

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Abstract This article presents a survey on hypermobile robots – a group of articulated mobile robots that typically comprise of several segments with powered wheels, tracks, or legs to propel the vehicle forward. Segments are connected by 2- or 3-degree-of-freedom (DOF) joints that may or may not be powered and provide better mobility as compared with regular mobile robots. The origins are analyzed and over 14 projects are compared in order to find the best methodology of designing and developing hypermobile robots.

Keywords Hyper mobile robot · Construction and control

1 Introduction

Urban search and rescue, industrial inspections, and military intelligence have one need in common: small-sized mobile robots that can travel across the rubble of a collapsed building, squeeze through small crawl-spaces to take measurements, perform visual inspections, or gather intelligence. Some of the aforementioned places are not only difficult to reach, but may also present safety and health hazards to human inspectors. One species of mobile robots that promises to deliver such hyper-mobility is the so-called hypermobile robot.

According to the Pocket Oxford Dictionary [1] the prefix hyper- (from Greek huper) means over, above or beyond, in this case suggesting mobility above normal level or abilities exceeding the behavior of regular mobile robots.

1.1 Definition

Hypermobile robots typically comprise of three or more rigid segments that are connected by 2- or 3-DOF joints. Typically, the segments have powered wheels, tracks, or legs to propel the vehicle forward, while the joints may be either powered or unpowered. The desired capabilities for such a robot are [2]:

- ability to traverse rugged terrain, such as concrete floors cluttered with debris, or unfinished floors such as those found on constructions sites;
- ability to fit through small openings;
- ability to climb up and over high vertical steps;
- ability to travel inside and outside of horizontal, vertical, or diagonal pipes such as sewage or ventilation channels, electric conduits or water pipes;
- ability to climb up and down stairs;
- ability to pass across wide gaps.

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2 Articulated Mobile Robots

Shigeo Hirose pointed out that there are three fundamental types of locomotion in the mobile robots: (1) wheels and crawler track, (2) legs, and (3) an articulated body [3]. Mobile robots can be designed using only one of these basic configurations or some combination of them. This section will focus on the latter case.

Articulated body mobile robot consists of several segments serially linked, resembling snake's anatomy. Such a robot can travel through rough terrain and overcome obstacles much higher than the robot itself by actively or passively adapting its long body to the topography of the ground. It can cross a ditch by stiffening the joint servomechanisms to bridge the gap. At the same time, it can stably wade a marsh by softening the joint servomechanisms to distribute its weight to all segments. In addition to high mobility, due to its slender body, the robot can crawl into narrow spaces or pipes for inspection or search and rescue missions. Moreover, the unified redundant structure may increase the reliability and maintainability of the mechanism. However, the generation of the undulating propulsive motion requires a large number of articulations (usually more than 10) and synchronized shifting of the bending motion from the frontal segment to the rear. Fortunately, practical mobile robots can be developed with a smaller number of articulations and a combination of wheels, tracks, or legs.

These extensive abilities of articulated mobile robots caught the attention of researchers in relatively few laboratories, comparing to the vast number of the laboratories working on mobile robots in general. In spite of the fact that the design of such robots is difficult and resource consuming (the building of many identical segments and joints), there are several working prototypes and a few practical applications of these robots shown in this survey.

3 Hypermobility Before Robots

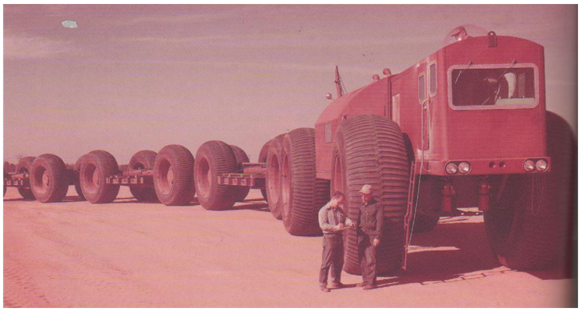


Fig. 1 One of the LeTourneau trackless trains LCC-1 [4]

The idea of joining several wheeled vehicles into a train to improve the traction of such a structure was used even before the appearance of the first mobile robot. Numerous machines that were similar to small trains for off-road navigation and used active wheel drives were built in the mid-1950s. The largest of these were huge land trains from R.G. LeTourneau Inc, shown in Fig. 1, built to access the most remote sites of the arctic and to dwarf just about any other land vehicle in both size and core strength, as presented in [4]. Originally conceived to assist logging in trackless wilderness, LeTourneau, famed for its earthmovers, devised the first of its land trains, the VC-12 Tournatrain, in 1953–1954 with a lead cab and three trailers. A 500 hp Cummins diesel engine powered a generator that fed electric motors at each wheel, thus spreading the power application across 16 wheels to enhance traction. A later iteration of the Tournatrain added a second Cummins engine and four more trailers to put 32 drive wheels to the ground. Steering was easy – each car automatically tracked behind the control car, while the driving thrust of each car was teamed with the others to keep the whole carrier moving – as reported by [5].

4 Review of Hypermobile Robots

Hypermobile robots appeared in the early 1990s, but most of the practical applications derive from more recent projects. It is also noticeable that most of the constructions come from only a few laboratories or research centers where whole families of hypermobile robots have been developed. One situation where hypermobile robots could play the leading role is search and rescue. The intensified work on this field was related to large catastrophes which occurred in different countries: the Kobe earthquake, terrorist attacks of 9/11 and bomb attacks on trains in London and Madrid. Another important application for hypermobile robots is an inspection task in sewage systems, gas pipes or venting systems. Let's look at the chronological review of the most important projects in this field.

The first working prototype of a hypermobile robot, called Koryu or KR-I, was introduced by Hirose and Morishima in 1990 [6] and later improved with version KR-II [7], as shown in Fig. 2. KR-II was developed with premise that it will be applied as a mobile robot for an atomic reactor. It was also considered to be used as a substitute for fireman in rescue operations such as: patrolling, gas detection, inspection and human salvage. This first hypermobile robot was large and heavy, weighing over 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 allowed a segment to lift its neighbors up, in order to negotiate steps or span gaps. Each segment of KR-II was equipped with a single wheel, arranged in a way that the unit with the wheel on the right side will come after a unit with the wheel on the left side. At first glance, this single wheel design may seem unbalanced but its stability was secured as the segments were linked. Especially, if the vehicle was in a zigzag configuration. Moreover, this single wheel design has other advantages:

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

These robots inherited all the abilities of hitherto developed snake-like robots:

- they can move along irregular terrain with sharp height altitudes and tight curves – thanks to the combination of the very short rigid links with a large density of joints,
- they can cross over crevasses by holding the body stiff acting as a bridge,
- in marshy and sandy terrain, they can move by distributing force through the entire body length.

Active crawlers or wheels mounted on each segment additionally give further advantages:

- high speed motion – direct propulsion is more effective than undulation,
- high load capacity – a simple driving system in each segment enables high loads to be carried,
- good portability – each unit can be detached from the robot for transportation,
- high reliability, because it is made redundant – broken segments can be easily replaced and special segments could be added depending on the mission,
- versatility of the body motion – Koryu can be used not only for "locomotion", but also for "manipulation" – as claim the authors [8].

For the motion control of the robot with several wheels touching the ground the passive compliance or the force sensors which detect reaction

Fig. 2 Koryu robots: KR-I (*left*), KR-II (*right*). Hirose Fukushima Lab, Tokyo Institute of Technology

Fig. 3 Snake2 developed at the GMD (now Fraunhofer IAIS)

forces are indispensable. As for Koryu, a special construction of optical force sensors was introduced. Such sensors were mounted in both vertical and horizontal axes to control the robot both among obstacles and on uneven terrain. The detailed description of steering method and attitude control can be found in [9].

Further developments in the same laboratory at the Tokyo Institute of Technology led to the concept of a group robot called Gunryu [10]. The group consists of tracked mobile robots equipped with 6 DOF manipulators, and can work in several modes. Each vehicle can operate as a single device, a few of them can cooperate in joint tasks or can be interconnected by manipulators in the chain-like structure. The later mode is an example of a hypermobile robot and can benefit the most from the chain structure. Namely, Gunryu is able to pass trenches wider and climb slopes steeper than single mobile robot could do – as presented in [10].

In 1999, at the German National Research Center for Information Technology (GMD) in Sankt Augustin, Klaassen and Paap [11] developed the Snake2 vehicle, consisting of six active segments and a head, as shown in Fig. 3. 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 electrical 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. In rectilinear locomotion, snakes propel themselves using unidirectional travelling waves of muscular contraction and anisotropic friction provided by these scales [53]. This type of motion is useful in the confined spaces. Snake2 was specifically designed for the inspection of sewage pipes.

Another hypermobile robot designed for sewer inspection was developed in Germany at the Forschungszentrum Informatik (FZI) in cooperation with GMD and two other German companies [12] This project called MAKRO (the acronym of Mehrsegmentiger Autonomer KanalROboter, in Eng. Multi-Segment Autonomous Sewer Robot) was funded by the German Federal Ministry of Research (BMBF) and produced the whole family of inspection robots shown in Fig. 4.

Initially, the first version of the robot i.e. MAKRO 1.0 uses two independent wheels; whereas the wheels in successive versions have common drive and stiff axel. Actuated 3 DOF joints allow full control over each segment's spatial orientation, which is crucial to preserve optimal traction for all wheels. Joints are strong enough to lift up two front or rear segments. The robot is able to work in ducts with diameter 300–600 mm, negotiate tight 90° angled pipes, climb up the ramp with inclination 27°, and surpass obstacles with heights up to 35 cm. One segment and its joint are about 20 cm long each.

MAKRO 1.1, shown in Fig. 4, is an autonomous service robot that can be used for a whole range

Fig. 4 MAKRO robots for sewer inspection (from *left*): MAKRO 1.0, MAKRO 1.1, MAKROplus (reproduced from [15, 51])

of specific duties within a sewage system. The basic version consists of 6 segments and 5 joints; its length is 160 cm and weight 30 kg. MAKRO carries all the necessary resources on-board [13]. The robot has a symmetrical construction with head segments at the ends. Both of them contain a video camera, structured light source, IR scanner and ultrasound sensor [14]. Four-level hierarchical control system is proposed to autonomously drive the robot inside sewage pipes [15]. The robot's mission is specified by a human operator who determines the entry and recovery points and downloads a map of all pipes and manholes in the inspection area. Then the planning algorithm generates the sequence of actions, which are executed by an action controller. Movements of all actuators have to be precisely synchronized to avoid perilous tilting or getting stuck on the curve. In case of obstacle detection, blockage or malfunction, the planner automatically finds a new set of actions.

The development of sewer inspection robots has been continued in the joint project MAKROplus. "The underlying concepts of the robots are identical, but MAKROplus will be water and explosion proof, and will have two special application segments for inspection tasks. The robot will be even twice as fast (maximum of 60 cm/s), the electronic hardware used (processor, hard disk) is more advanced and powerful. The battery also lasts longer, now able to give power twice as long" – reported constructors in [15]. The MAKROplus prototype was tested in the waste water system of the city of Siegburg under real operational conditions and is available through Inspector Systems Rainer Hitzel GmbH.

A similar transformation in the design from serpentine robot undulating on the flat terrain to hypermobile robot with active wheels may be observed in the family of ACM robots from Hirose Lab. While the early versions were standard snake-like robots, in their fourth construction Yamada & Hirose introduced active wheels concept [16]. Snakes themselves have several hundreds of joints, while several tens of joints are the practical limit with current snake-like robots, and this certainly limits maneuverability. With active wheels, however, the robot can move even with minimal ground contact, enabling propulsion over irregular terrain with the limited number of joints. The robot can also advance in a straight line without serpentine motion, making the operation much easier – remarked the authors [16].

"It is desirable to have snake-like robots that can move in environments like pipes that have long straight narrow sections and also bent sections. The introduction of bending and elongating joints is one of the solutions, but adding active wheels can also solve the problem. The snake-like robot ACM-R4 (Fig. 5) has active joints and active wheels and was developed based on such a perspective" – say the authors [16]. This robot consists of nine joint sections; it is 1.1 m in length and weighs 9.5 kg; has a great ability to go over obstacles when compared to other type of robots with passive wheels.

Later on, this construction evaluated to the version ACM-R4.1 with water- and dust-proof segments and torque sensors in joints [17]. These sensors and the new control algorithm further improved mobility of the robot, by actively keeping all wheels on the ground, even in rough terrain. As showed the experiments the simplest way to reach this goal was keeping zero value for torques in all pitch joints of the robot.

There are several examples of vehicles designed for long-distance in-pipe inspection. Ryew et al. presented an in-pipe inspection hypermobile robot, shown in Fig. 6, capable of running at least 500 m per launch and selective navigation in branches [18]. This robot has an articulated structure containing: two active driving vehicles located in the front and rear of the system, passive modules such as a control module and other op-

Fig. 5 ACM-R4 robot (Hirose Fukushima Lab, Tokyo Institute of Technology)

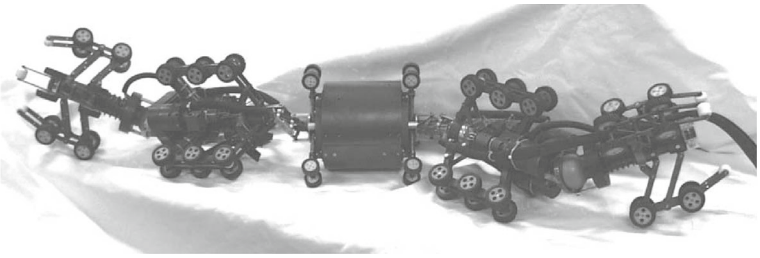


Fig. 6 In-pipe inspection robot with active steering mechanism [45]

tional modules that are linked between the active vehicles, and a tether cable.

"The presented robot has several characteristic features superior to the others such as flexible wheeled leg mechanisms, and a steering mechanism with compliance control" – claim the constructors [18]. A wheeled leg employs a pantograph mechanism with a sliding base that permits the natural folding and unfolding of the leg. In order to keep adequate pressure on the walls, three such structures are circumferentially spaced apart by 120° on the main shaft of both sections of the active vehicle. These sections are connected by a steering mechanism called double active universal joint that has 2 DOF working in active or passive modes with a stiffness control. It intrinsically prevents the rolling of the robot along the driving direction and enables to control its compliance. "Those features provide the robot with excellent mobility inside the highly constrained space while negotiating the complicated configurations of the pipeline networks" – conclude the authors [18].

While wheeled serpentine robots are efficient enough in smooth-walled pipes, rugged terrain benefits from tracked propulsion. To this effect Takayama and Hirose [19] developed the Souryu-I crawler, which consists of three segments, as shown in Fig. 7. In the first version, each segment was driven by a pair of tracks, which, in turn, were all powered simultaneously by a single motor, located in the center segment. Torque was provided to the two distal segments through a rotary shaft and universal joints. Each distal segment was connected to the center segment by a special 2 DOF joint mechanism, which was 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

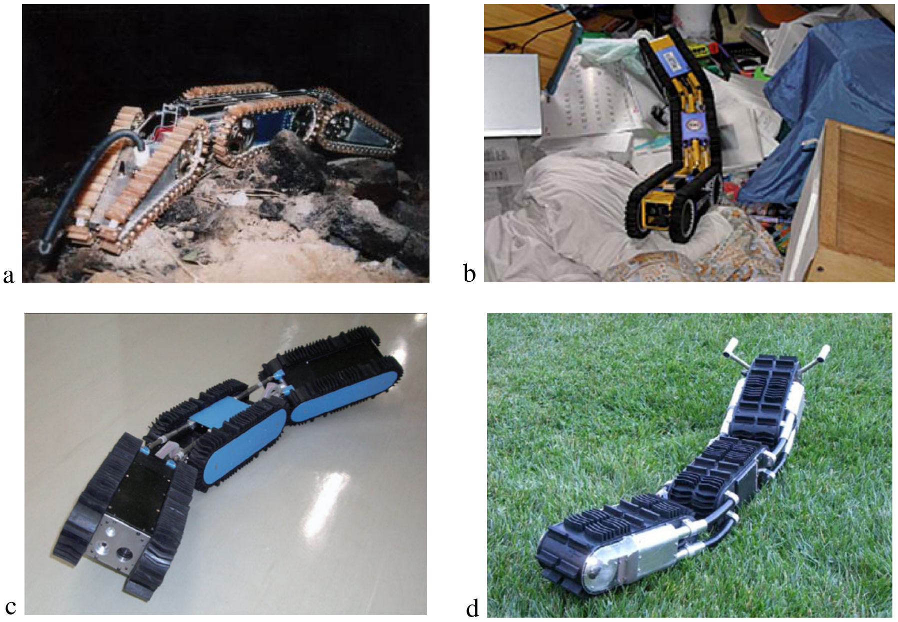


Fig. 7 Souryu robots:
a – Souryu-I,
b – Souryu-III,
c – Souryu-IV,
d – Souryu-V (Hirose Fukushima Lab, Tokyo Institute of Technology)

in yaw and pitch symmetrically to the center segment. Coordinated rotations of these joints can generate a roll-over motion of the robot. One interesting feature of this robot is the ability to adapt to irregular terrain because of the flexibility of its joints. It is provided by springs and cannot be actively controlled.

The next incarnation – Souryu-II was designed to easily separate three bodies so as to make them portable and to make it possible to add segments with special functions. The robot is equipped with a video camera and batteries, and may be remotely controlled.

The minimal driving system utilized since the first version was modified in Souryu-III. Each body consists of two standard tracks which are concurrently driven. Joints can make yawing and pitching motions, and are passively flexible while rolling. As a result the whole vehicle has five motors with dust- and waterproof covers for the internal components [20].

Based on the experiments of Souryu-I, II, and III on real sites, not only a novel crawler track has been developed using steel belt, but also the design of the crawler placement was reconsidered. The authors proposed two different configurations: independently actuated double-sided crawler, and mono-tread crawler, respectively, applied on the new Souryu models “Souryu-IV” and “Souryu-V” [21], as shown in Fig. 7.

Novel “Metal-Reinforced Crawler Track” has both a lightweight and great strength, due to the thin steel belt, moreover, the driving resistance of the belt is also greatly reduced – as highlight the authors [21]. They propose two grouser patterns on the tread: a thick block-type grouser, and a thin V-shaped grouser. As the experiments showed, the usage of both patterns simultaneously is a very effective solution in order to improve the crawler capability to overcome higher obstacles. When the track encounters an obstacle, the thin grousers bend and the obstacle goes ‘into’ the thread, then the thick grouser grips the obstacle. Therefore, the vehicle can climb obstacles larger than the radius of the crawler idler.

Authors also compare the results of two crawler configurations: a vehicle with independently actuated crawlers on both sides has good controllability, while the mono-tread crawler has good terrain traversability and is, from the mechanical point of view, simpler. Unfortunately, the application of mono-tread crawler is difficult, since any joint mechanism or other devices can be installed only on either of its side surfaces, what leads to a more complicated design. In order to address this issue, a special unit was designed, consisting of four elastic rods and rod-shortening/lengthening mechanisms on both sides of the crawler’s body. Due to the flexibility of the rods, which can absorb shocks, additional mechanisms for shock-absorption are not needed. Furthermore, the shock-absorber in the longitudinal direction and around roll, pitch and yaw axes, as well as the deflection of the elastic rod caused by the weight of the vehicle, make it easy to adapt the external body shape to uneven terrain.

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 [22]. This robot consists of seven electrically driven, very compact segments, as shown in Fig. 8. The diameter of the track sprockets is larger than the height of each segment, which allows the robot to drive upside-

Fig. 8 Prototype of Millibot Train: detail of a single module 3 cm high × 5 cm wide × 10 cm long (*left*), seven modules climbing a double-height (33 cm) step (*right*), The Robotics Institute, Carnegie Melon University

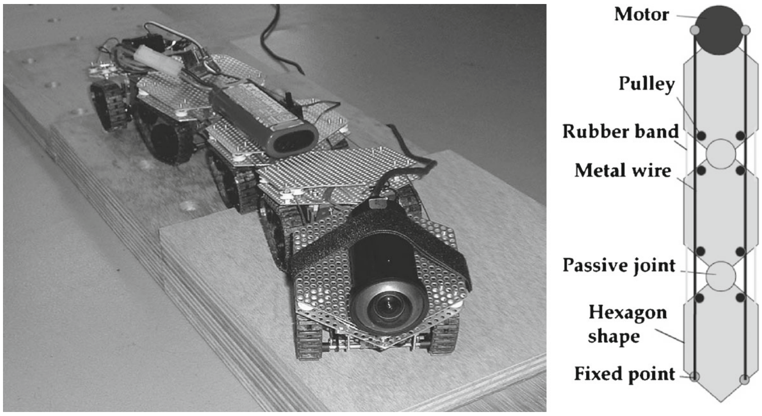
Fig. 9 Genbu representing group of active wheels – passive joints robots (Hirose Fukushima Lab, Tokyo Institute of Technology)

down. The 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 different concept using unpowered joints was introduced by Kimura and Hirose at the Tokyo Institute of Technology [23]. That robot, called Genbu (see Fig. 9), is one of the very few serpentine robots with unpowered joints only. The stability of the robot and its high mobility on rough terrain are preserved by large-diameter (220 mm), independently driven, wheels. The control system employs position and torque feedback sensors for the passive but relatively rigid joints. Springs are used to protect the electric motors from impact, although the stiffness of the springs cannot be controlled during operation. The robot was intended mainly for two applications: as a fire-fighting robot to pull a fire hose or as a planetary rover. In the first case wheels were driven by hydraulic motors powered by water delivered by the firefighter pump.

An interesting idea of mechanical intelligence for steering serpentine robot with only passive joints was presented in [24]. The prototype of the robot being able to realize semiautonomous control by mechanical constraints instead of computational intelligence is composed of several hexagon-shaped tracked vehicles connected by passive joints and additional metal wires linking gears mounted on both sides of each module, as shown in Fig. 10. Whenever any part of the robot's body encounters an obstacle, the wire length on each side varies automatically (as the joint nearest to the obstacle rotates), and then changes the shape of the robot's body, in order to avoid the obstacle. In the proposed mechanism, the reactive force from the obstacle is used directly, so no tactile sensor is necessary. Rubber bands to generate restorative force are attached between passive joints. The wire length on each side can also be adjusted by a motor in order to change the direction of motion intentionally. "The mechanical intelligence based snake rescue robot has a light body, low price and low computation cost" – underlined the authors [24]. The user interface proposed here is also very intuitive: steering wheel

Fig. 10 Concept of mechanical intelligence for serpentine robots: prototype of the robot (*left*), steering architecture (*right*), [24]



with force feedback to change robot's direction, two pedals to regulate the speed of the crawlers, stereo headphones and a set of six LCD monitors arranged as windows give the feeling of driving a car. Although the described mechanical intelligence worked only in a horizontal plane, Ito and Murai presented additional modification allowing the robot to traverse steps, gaps and even stairs [25]. The improved versions were presented recently, radio controlled in [26] and autonomous, vision controlled in [27].

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. [28], and shown in Fig. 11. This robot contains 8 segments of different structure and function: two distal segments have CCD video cameras mounted but have no propulsion means, the second units have right and left crawlers which are driven together, the other segments also have right and left crawlers but independently driven. There is also a variety of joints implemented in this design:

- two 2 DOF joints driven by simple RC servos to control the position of the heads with video cameras,
- two 2 DOF joints with powerful DC motors and linkages to rise two segments on either end, which improves the capability of overcoming obstacles,
- three 3 DOF 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.

This robot implements a smart design feature: besides a video camera in the front segment, there is a second video 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. The operators use Sony gamepads as user inputs and a monitor with specially organized views from the video cameras. The authors proposed an algorithm (based on robot kinematics only) calculating the speed of tracks and rotation of joints in order to realize the follow-the-leader control.

KOHGA with its passive joints has a vital problem that obstacles can be caught in the joints and then the robot will be stuck. To solve it, the new reconfigurable version of KOHGA 2 was developed [29]. The unit structure consists of: the crawler-arm-unit (with motor and the crawler belt), the joint-unit (1 DOF), the terminal-unit (to mount sensors at the distal ends of the robot) and the connecting part (that has 4 axes to possibly mount crawler-arm-units in various arrangements). The robot can work as a self-contained module or can be connected to other units creating a multi-segmented vehicle. 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, (2) the robot with crawler-arm-units mounted coaxially is more effective to the stuck avoidance than the non-coaxial type because is symmetrical and therefore more stable, and (3) the propulsive power of the robot should be improved by changing to the wider crawler belt.

Fig. 11 Robot KOHGA (*left*), KOHGA 2 in a few configurations, KOHGA 3 (*right*), Matsuno Lab., Kyoto University

A serpentine robot that uses tracks for propulsion and pneumatics for joint actuation is MOIRA shown in Fig. 12, and described in [30]. MOIRA consists of four segments, and each segment has two longitudinal tracks on each of its four sides, for a total of eight tracks per segment. All tracks are powered by 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, the robot is insensitive for rollovers and with additionally cone shaped distal segments it can dig into the debris surrounded with obstacles. The 2 DOF joints between segments are actuated by pneumatic cylinders. While MOIRA can lift up its segments high enough to overcome obstacles, it can also decrease the stiffness of actuators to nicely conform to the ground. The robot is controlled by a specially designed control box containing 3 joysticks and several switches. There is also a view from the nose, transmitted via USB by a CCD video camera.

After several experiments in the rubble environment, constructors of Moira identified some real problems:

1. The ratio of covered section with crawlers is too small and therefore the robot is prone to get stuck on some narrow obstacles e.g. while crossing a bank or climbing up the stairs, as soon as the obstacles catch a joint. The overall length of the sections where the crawlers are present is 80 cm and that of the joints is 63 cm. 56 % of body length is equipped with crawlers. If this percentage is low, the possibility of getting stuck in the rubble increases, what confirms one of our doctrines in the design of OmniTread, as presented in Section 6 (our policy is even stronger as we consider ratio of respective surface areas instead of lengths).
2. The symmetrical cross section of the body module caused the problem that the robot tends to roll. Particularly, when the MOIRA raises the head to surmount the obstacle, many upsets occur. This immensely affects the ability of climbing.
3. The timing belt and pulley are used at the MOIRA as the crawler mechanisms, and no measures are applied to prevent small gravel, dirt or debris being caught by the mechanism. Therefore, when the robot moves to an outdoor field, there is a strong possibility of a jam.

To address these problems the new version MOIRA 2 was designed and built [31]. The robot still comprises of four segments: a head, two middle segments and a tail, connected by 2 DOF pneumatically driven joints, as shown in Fig. 12. Segments can be easily detached for transport and then recomposed quickly in the field. The length of the joint was drastically shortened (comparing

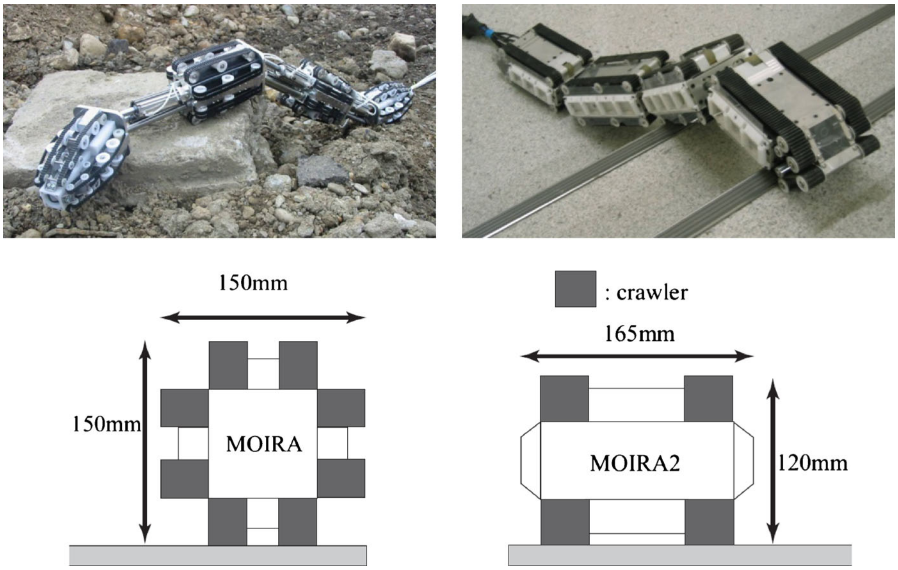


Fig. 12 Robots MOIRA (*left*) and MOIRA 2 (*right*), comparison of the cross section of robots (bottom row), Osuka Lab., Osaka University

to MOIRA) by relocating pneumatic cylinders inside the segment. The percentage of body length equipped with crawlers increased from 56 % to 90 % improving robot's traction. Also the shape of the robot was modified by: (1) changing cross section from square to rectangular and (2) leaving only top and bottom crawlers while replacing side crawlers by rollers, as presented in Fig. 12. These modifications improved stability (less chance to roll over) and simplified the construction of the robot (less tracks to drive by a single motor), as the authors reported. To address the third problem (with crawlers) new teeth profile, high flange pulleys and side covers were applied. Additionally, distal ends of the head and the tail segments are inclined and suitable shape to wedge into openings. Both versions MOIRA and MOIRA 2 are connected to power sources (electric and pneumatic) and control devices by cables and tubes.

The most recent construction from NREC (National Robotics Engineering Center) is the Pipeline Explorer – a robot designed and built for inspection of live gas pipelines [32]. This robot, shown in Fig. 13, has a symmetric architecture. A seven-element articulated body design includes locomotor (with camera) modules, battery carrying modules, support modules, and a computing (electronics) module located 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 by pitch-roll joints, while connections between other modules utilize pitch-only joints. These specially designed joints allow orienting the robot within the pipe, in any direction needed.

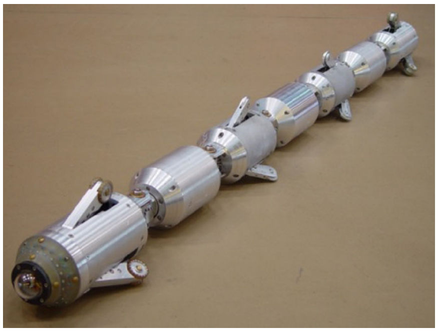


Fig. 13 Pipeline Explorer from NREC (National Robotics Engineering Center)

The locomotor module houses a mini fish-eye video camera, along with its lens and lighting elements. The video camera has a 190° field of view and provides high-resolution color images of the pipe's interior. The locomotor module also houses dual drive actuators enabling the deployment and retraction of three legs equipped with custom-molded driving wheels. The robot can sustain speeds of up to 0.1 m/s. It is fully untethered (battery-powered, wirelessly controlled) and can be used in explosive underground natural gas distribution pipelines. The construction of the 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 (including the author of this paper) introduced the whole family of hypermobile robots called Omnis, shown in Fig. 14. 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 [33]. 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 [34]. The OmniTread design offers two fundamentally important advantages over its predecessor and, in fact, over all other serpentine robots hitherto described in the scientific literature. These features are: the maximal coverage of all sides of all segments with propulsion elements, and 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 [2].

This robot passed extended tests at SouthWest Research Institute showing excellent performance on the sand and rock testbeds, as well as in the underbrush. It can climb obstacles 2.5 times higher than itself and span trenches almost half

Fig. 14 The Omnis family of hypermobile robots: OmniPede (*upper left*), OmniTread (*lower left*), OT-4 (*right*), University of Michigan

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 [35]. The OT-4 is even more versatile than its predecessors, with onboard power sources (both electric and pneumatic) it can operate up to one hour, with wireless communication, thereby is completely tetherless, thanks to the clutches it can precisely control power consumption, and with additional flipper-tracks it can easily overcome the knife-edge hole obstacle (small opening in the thin wall, located high above the ground) and climb almost 5 times its own height. The detailed information on performance of all members of the Omnis family can be found in [36].

A reconfigurable hypermobile robot was developed by Zhang et al. as reported in [37]. The JL-I system, shown in Fig. 15, 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. Additionally, each module is equipped with two parallel mechanisms (to realize pitch and yaw movements by ±45°) and serial mechanism (for rolling movement; 0–360°), which can form active 3 DOF spherical joint to enable the robot to change its shape in three dimensions, and achieve highly adaptive locomotion capabilities. 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 the assembled robot. Each module is an autonomous mobile robot capable of performing basic tasks such as search and navigation. In order to realize 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. The robot has shown the ability to climb onto steps, span gaps and recover from any rollover situation.

About the same time came our own project realized at the Lodz University of Technology [38]. We considered an articulated mobile robot called Wheeeler and presented in Fig. 16. Our goal

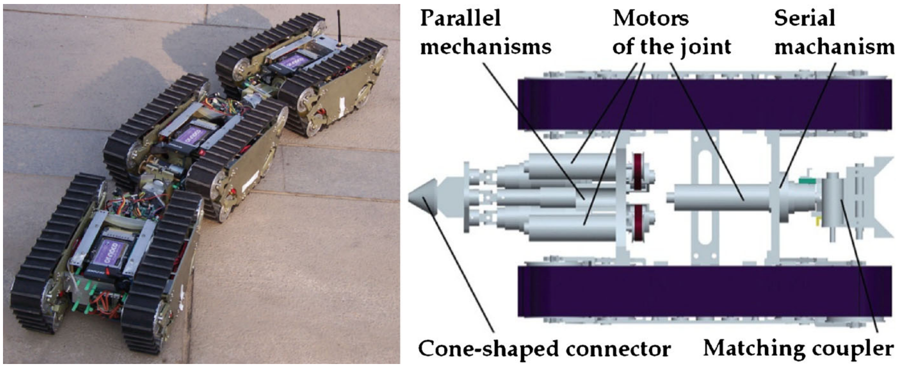


Fig. 15 Reconfigurable robot JL-I (University of Hamburg)

Fig. 16 Prototype of Wheeeler

was to simplify teleoperation of the articulated mobile robots and increase their applicability.

Wheeeler follows the typical modular structure of hypermobile robots. It consists of six, geometrically identical segments. Each segment has an actuated axle with two wheels and a passive suspension. On each of the two ends of a segment, there is a 1 DOF actuated joint, to be connected to the following segment, or in case of the robot's ends – to attach a video camera. The assembled robot has 2 DOF articulated joints (allowing pitch and yaw rotations) between each two segments, and actuated wheels. This gives three control variables per segment and 18 in total.

Wheeeler is intuitively controlled by either a single 3 DOF joystick or gamepad, it is associated with 2 DOF joint between the first and the second segment of the robot and therefore controls direction of motion; throttle or additional buttons are used to set the speed of the first segment. We have compared two methods for coordination of segment movements: follow-the-leader and n-trailer. Wheeeler's performance under n-trailer control is better than in case of the follow-the-leader, as reported in [39].

A big step towards fulfilling the postulate of having a robot whose whole body generates propulsion is the creation of Wormy a flexible mono-tread (FMT) mobile track [40]. The vehicle is composed of a "flexible chain" and a spine-like structure. The robot is 1.2 m long, 0.2 m high and 0.2 m wide, and weighs 12.4 kg. FMT has only one track which wraps around the vehicle's body, which is able to flex in three dimensions and in fact, alter the original positions of its head part, as depicted in Fig. 17.

The authors adopted the backbone-like structure for the body of Wormy. "It consists of six segments as vertebrae and cylindrically shaped rubber materials are put between the segments as intervertebral discs. The flexible material allows a segment to rotate in small extent relative to adjacent segment around each of roll, pitch, and yaw axes. Thereby, the body, as a whole, flexes in shape symmetrically around yaw axis (which is *lateral flexion*) and around pitch axis (which is *retroflexion*), to make a smooth circular arc. By twisting around roll axis, the body conforms to rough terrain compliantly" – report the constructors in [40]. Actuators generating lateral flexion and retroflexion are located in both of the terminal segments, while the twisting motion of the body around roll axis is passive.

Wormy performs very well on various terrains and can cope with different obstacles: steps, gaps, slopes, stairs and even narrow plates. This robot can recover from lying on the side (without a tread) and can move laterally in a sidewinding motion.

We have to mention a Norwegian inspection robot PIKo, which is the natural continuation of the family of several snake-like robots [41]. The work of researchers from NTNU and SINTEF is

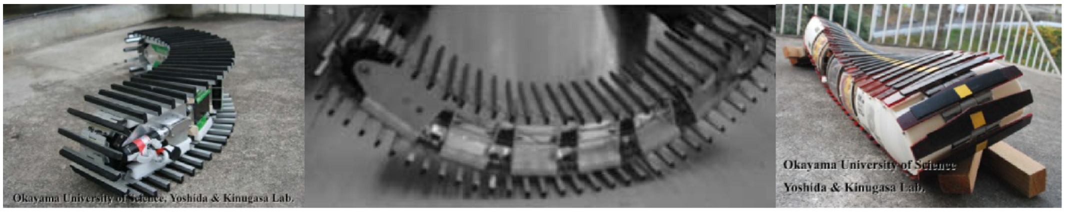


Fig. 17 Flexible mono-tread mobile robot RT02-WORMY (*from left*): laterally flexed, retroflexed, twisted (Yoshida & Kinugasa Lab, Okayama University of Science)

one of the most comprehensive projects of hypermobile robots: it contains the development of kinematic and dynamic model of the robot, simulation, design of mechanical construction, and comparative tests of various control methods on both the model and real robot.

PIKo consists of five identical modules interconnected by 2 DOF active joints, as shown in Fig. 18. A set of 4 active wheels on each module provides propulsion. Horizontal motion is achieved through a train-like scheme, while vertical motion is achieved through pressing modules against the internal walls when robot is in the zigzag configuration. The robot is able to navigate in pipe structures with varying dimensions and curvy configuration – as the authors report [41].

Authors have also presented a mathematical model of the dynamics of a serpentine robot with active wheels and the new path-following approach based on control strategies for n-trailer vehicles [42]. The dynamic model is based on a non-minimal set of coordinates which is advantageous for numerical treatment of the system equations during simulations. “Moreover, friction forces between the wheels of the robot and the ground surface are modeled as Coulomb friction and described within a framework of non-smooth dynamics and convex analysis” – the authors highlight in [42]. This allows describing “true” stick-slip transitions since the model can account for non-zero friction forces for zero velocities (i.e. during “stick-mode”). Coordination of many joints and wheel velocities of a serpentine robot was achieved in a passive-like manner which reduced the amount of necessary control torques – add the designers. Presented simulations showed that a 6-link serpentine robot was able to follow a set of various curves using the n-trailer approach. In addition, these results were compared with an implementation of a follow-the-leader approach. It was presented in simulations that the n-trailer-based path-following controller was able to follow a pre-defined path more closely for more complex paths in addition to requiring less total commanded torques. As an example, the authors showed over 40 % reduction in path following error and 20 % reduction in commanded torque for the 8-shaped curve.

Researchers from Matsuno Lab. at Kyoto University have recently developed the hypermobile robot using a screw-drive mechanism as reported in [43], to shown in Fig. 19.

Several (at least 3) cylindrical modules called left- and right-screw driving units are connected by 2 DOF active joints working in yaw and pitch directions. Each unit contains a ring (that can rotate around the longitudinal axis of the robot) with many passive wheels evenly distributed on its circumference and oriented at some specific angle α with reference to the foregoing longitudinal axis. This orientation determines whether the unit is called left (α is positive) or right (α is negative). The robot also has a special head with ball bearings preventing rotation of the entire robot around the longitudinal axis. Propulsion of the robot comes purely from a rotary motion of the rings in the screw driving units, this motion is transferred to the ground through passive wheels. The important feature of the screw-drive mechanism is that it propels the robot in the same direction (for the given rotation of the units) regardless the point of contact between mechanisms and the ground. Therefore, the robot should work correctly both on the flat terrain (the points of

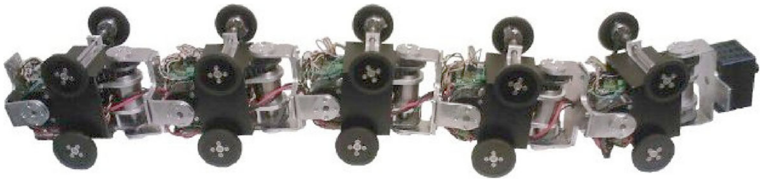


Fig. 18 Hypermobile robot PIKo: total length 1 m, width 0.13 m, height 0.14 m, weight 6 kg, max. speed 0.2 m/s, (SINTEF and NTNU)

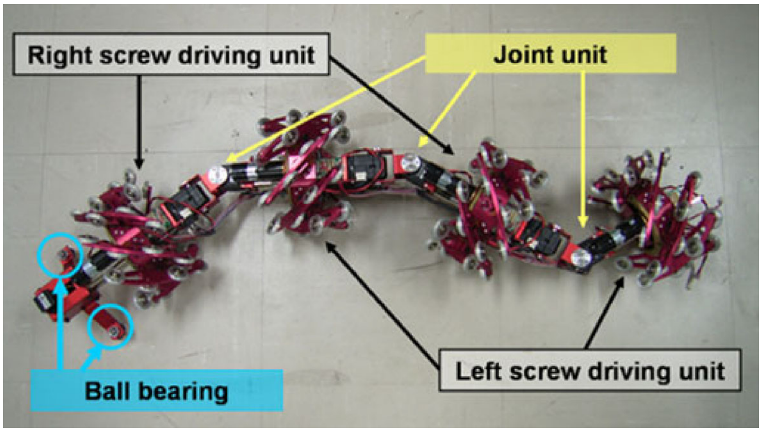


Fig. 19 Hypermobile robot using screw-drive mechanism (reproduced from [43])

contact are on the bottom of the robot) and in the confined spaces (obstacles can touch the robot from different sides).

At the end of this review we have to mention the newest Souryu robots from Hirose Lab., shown in Fig. 20, [44]. They inherited structure partially from Koryu II – robots consist of many segments, each of them has only one wheel and neighboring segments have wheels on other sides – and partially from previous Souryu robots – joints are coupled. Souryu-VII has 8 rigid segments and 7 elastic segments (rubber made). There are four active wheels on the same side and they rotate with the same speed. There are three metal wires passing through all segments from the head to tail. They are fixed on one end to the head segment and can be pulled by the driving mechanism mounted in the tail. Therefore robot has 5 controllable variables in total and performs limited spatial movements. With the next version – Souryu-VIII – authors have addressed a few important problems, namely: limited bending angle, bottom side only operation, high friction between wires and the robot's body, and elongation of the wires when external forces are applied. Moreover, the new robot is much lighter. Souryu-IX looks like two Souryu-VIII robots connected serially by roll joint located in the center of the whole structure. This operation gave the new advantage – one section can rotate 90° and provide propulsion on the side surface of the robot, i.e. on the surface that normally cannot generate effective traction force. To keep the robot light-weight and less complicated the authors removed the wire driven bending mechanism from the rear section and therefore this section is passively following the frontal part of Souryu-IX [44].

5 Control of Hypermobile Robots

As we observed from the literature review, the variety of mechanical constructions of hypermobile robots meets almost the same variety of control methods presented by researchers. No doubt that the task is very challenging as we have many (usually more than 10) local variables to regulate in the synchronized manner. Most of the hypermobile

Fig. 20 Souryu-VII (*left*) and Souryu-VIII (*right*), reproduced from [44]

robots presented to date lack the autonomy or this autonomy is limited to very specific environment of operation [15, 45]. However, starting from the very first hypermobile robot authors try to make the teleoperation task as intuitive and easy as possible. We can distinguish at least three approaches: proof-of-concept systems with simple controller, mathematical modeling and control synthesis, and artificial intelligence to support operator.

To start working every robot requires some control system but to prove the concept in most cases they employ multi DOF joysticks [30], have synchronized joints that follow mechanical constraints [20, 21, 25, 45], or need a few human operators (two in case of OmniTread [34], three for OT-4 [35]). Further developments to ease the job of the operator of hypermobile robots continued in two directions: designing specialized haptic devices to support the operator and using software-based aid.

5.1 Joysnake

In order to reduce the number of operators needed, Baker and Borenstein [52] developed a "Haptic Operator Console" (HOC), which they call the "Joysnake" (as in joy-stick.) The premise of the Joysnake is that the fastest and most intuitive method for a human operator to command a pose for a High Degree of Freedom robotic mechanism is to shape an adjustable replica of the mechanism into the desired pose. From the simplest to the moderately difficult tasks the Joysnake works sufficiently well to replace the three operators by just one. However, in highly complex tasks the three operators perform better.

The second approach to help the human control hypermobile robots is to develop assisted remote operation, in which the operator sets the overall goal direction and does medium scale path planning but is assisted by automated control of most of the robot's degrees of freedom. In this approach a human operator, viewing a video display from the camera and other sensor data, controls the movements of the head of the robot while an automated system controls movements of the rest of the robot's body to customize them (using sensor data) to the conditions of the local terrain. This requires mathematical modeling of the robot's kinematics and dynamics, sensor fusion to estimate state of the robot, or artificial intelligence to teach complex behaviors.

5.2 Coordination Methods

There are two well-known methods to coordinate the movements of several segments of articulated mobile robots, namely: follow-the-leader and n-trailer. The first approach also known as a "shift control" utilizes a very basic principle: all modules should repeat the pattern of the first module – the leader – at the exact same spatial position as the leader module. This method was used in the defined form in a few projects [13, 15, 16, 28, 38, 41] and worked the best for the robots with short intersegment lengths. In the other cases deviations from the trajectory of the leading segment and sideslip of the wheels (or tracks) are inevitable. Some improvement in the path tracking may be obtained when the shift role is modified as suggested in [9, 46], or [47]. In the first paper the authors derived two proposals: (1) taking the average value of the foremost segment's control angle over the time to travel a certain distance as the next segment's turn, and (2) calculating the control angles of all joints based on the geometric relationship assuming that each segment's center is considered to travel along a given desired trajectory. The second solution presented the best trajectory tracking performance and energy efficiency while the former one less computational demand and therefore fits better to the real-time applications. The authors of paper [46] used the strategy similar to the proposal (2) above but they assumed that the spatial position of each joint will track the trajectory of the first joint, which is steered by an operator. Using Frenet frames to describe geometrical relations and estimating tracking error based on the passed velocity commands they proved convergence of the proposed method even if the curvature of the target path change. It is also possible to derive some heuristic patterns of shifting the joint angles and the velocities while robot is moving [47], however, this method seems to be less universal than the others.

The n-trailer method is related to the steering of a truck pulling n trailers linked behind it. Physically it is similar to a wheeled multi-joint robot but with some important differences. The n-trailer system has only one active module, the truck that can change its orientation and velocity, while all the trailers are passive. In contrast, hypermobile robot has several modules with both the joints and the wheels active. Nevertheless, the kinematic analysis of the n-trailer model leads to the control algorithm (for all joints and wheels of the articulated mobile robot) that moves the robot as if it actually was being pulled by the virtual truck. What is more, since the trailers of the n-trailer system behave in a passive manner, this control scheme should result in an equivalent "passive" behavior of the hypermobile robot. This means that in the ideal case, the aforementioned slip of the wheels will be eliminated. Both follow-the-leader and n-trailer methods were tested in our Wheeeler project [39] and also comprehensively compared on PIKo robot [42]. They work reasonably well on an uneven but still continuous terrain, unfortunately, control on stairs requires further improvements.

An assumption being crucial for the coordination methods is that we know the speed of the robot with reference to the ground. It may be particularly hard to meet this condition on the rocky or slippery grounds. A few solutions can be found to help this problem:

- avoid slippage by active [2, 8, 11, 17] or passive joints [23, 28, 44], or additional elements [32, 38, 45] that provide good trafficability of the robot – maximize tractive power,
- detect slippage and estimate true value of the speed [39, 48].

5.3 Artificial Intelligence to Assist Teleoperator

Hutchison et al. proposed the use of the Seventh Generation (7G) Control System to develop a control system for the OT-4 robot [49]. The work focused on controlling the OT-4 robot as it moved through several challenging terrains:

- stairs of various configurations,
- parallel bars with random separations and heights, including wide gaps,
- a level slalom course among rocks, and
- stairs with rock obstacles.

"A specific objective of the control development effort was to develop a single control system that would handle all terrains automatically, including transitions between them, instead of developing specialized control for each terrain" – said the authors [49].

The 7G Control System includes a neural network for reinforcement learning (RL), a customized genetic algorithm to optimize agent and training parameters and an automated training system. The core of the system, the 7G Robot Control Agent, is a reinforcement learning system implemented as a fully connected neural network for state-action value function approximation.

"The performance of the real OT-4 robot under 7G control in all before mentioned scenarios: on stairs, parallel bars, a slalom course, and stairs with obstacles corresponded well to the simulated performance on which development of the control system was based" – the authors concluded [49].

6 Conclusions

The extended literature review presented above was done in order to analyze methodologies used in designing and building hypermobile robots. We have also included our own experience in this field coming from the Omnis project and the recent Wheeeler development. The most important information about each hypermobile robot is summarized in Table 1.

Hypermobile robots have the potential to provide hitherto unattainable capabilities, such as moving in an unstructured environment, climbing over high steps, traveling inside horizontal or even vertical pipes, or traversing wide gaps. While individual tasks of this nature have been tackled in the past by special-purpose mobile robots (e.g., pipe crawlers), it appears that only hypermobile robots may be able to perform a large variety of difficult tasks.

In this survey we have presented several concepts of hypermobile robots, in most of them designers used tracks for propulsion, as they give the robot flexible mobility in rugged terrain in

Table 1 Basic properties of hypermobile robots, CAC – computer aided control, NA – information not available

Feature\Robot	KR-II	MAKRO 1.0	MAKRO 1.1	Souryu I	Souryu V	KOHGA
Number of segments	7	5	6	3	3	8
Length [cm]	330	160	200	116	116	205
Height [cm]	108	18	21.2	14	14.5	13.5
Width [cm]	46	20.3	19.5	17.5	20.2	18
Weight [kg]	320	30	49	10.2	16.5	18
Joints	2DOF, active electric	3DOF active electric	3DOF active electric	3DOF active electric	3DOF	2DOF active electric, 3DOF passive
Propulsion	wheels	wheels	wheels	treads	treads	Treads
No of propulsion means per unit	1	2	2	2	1	2
Speed [cm/s]	50	60	30	15	NA	5
Adapting to rugged terrain	Active control of joint	Active control of joint	Active control of joint	Passive joints	Passive joints	Passive joints
Max slope to travel [°]	38	27	27	NA	NA	30
Types of operation	Remote control	Remote control, some autonomy	Remote control, autonomy	Remote control,	Remote control	Remote control, gamepad CAC
Max height of obstacle [cm]	38	35	35	42	64	15
[%] of robot height	35	194	194	300	440	11
Rollover sensitivity	One side only	One side only	One side only	Upside down	Upside down	Upside down
Low ceiling operation	Very limited	Limited	Limited	Limited	Limited	Limited

Table 1 (continued)

Feature\Robot	MOIRA	MOIRA 2	OmniTread	OT-4	JL-I	Wheeeler
Number of segments	4	4	5	7	3	3 (6)
Length [cm]	143	110	127	94	105	55.5 (111)
Height [cm]	15	12	18.6	8.2	15	11.5
Width [cm]	15	16.5	18.6	8.2	25	21
Weight [kg]	18	16	13.6	4	21	2.7 (6)
Joints	2DOF active pneumatic	2DOF active pneumatic	2DOF active pneumatic	2DOF active pneumatic	3DOF active electric	2DOF active electric
Propulsion	treads	treads	treads	treads	treads	wheels
No of propulsion means per unit	8	5	8	8	2	2
Speed [cm/s]	20	11	10	15	18	40
Adapting to rugged terrain	Natural compliance	Natural compliance	Natural compliance	Natural compliance	NA	Spring suspension
Max slope to travel [°]	34	NA	30	40	40	21
Types of operation	Remote control	Remote control	Remote control, 2 gamepads	Remote control, 3 gamepads	NA	Remote control, gamepad CAC
Max height of obstacle [cm]	38	NA	46	40	28	12
[%] of robot height	253		247	488	187	104
Rollover sensitivity	Four sides, insensitive	Upside down	Four sides, insensitive	Four sides, insensitive	Upside down	Upside down
Low ceiling operation	Unlimited	Unlimited	Unlimited	Unlimited	Limited/possible	Limited/possible

Table 1 (continued)

Feature\Robot	Wormy	PIKo	Souryu-VII	Souryu-VIII	Souryu-IX
Number of segments	6	5	8	10	18
Length [cm]	120	100	59.4	56.7	164.6
Height [cm]	20	14	11.1	6.8	9.6
Width [cm]	20	13	13.6	11.2	16.2
Weight [kg]	12.4	6	4.4	0.9	8.7
Joints	3DOF passive	2DOF active electric	2DOF active coupled	2DOF active coupled	2DOF active coupled, 1DOF active, passive
Propulsion	mono-tread	wheels	wheels	wheels	wheels
No of propulsion means per unit	1 common	4	1	1	1
Speed [cm/s]	NA	20	31.5	31.3	39.8
Adapting to rugged terrain	Flexible rubber	Active control of joint	Flexible rubber	Flexible rubber	Flexible rubber
Max slope to travel [°]	45	NA	32	35	39
Types of operation	NA	Remote control, gamepad	Remote control	Remote control, 2 gamepads	Remote control, 3 gamepads
Max height of obstacle [cm]	45	NA	18	18	31
[%] of robot height	225		163	265	323
Rollover sensitivity	Upside down	Upside down	Bottom side	Upside down	Four sides, after reconfiguration
Low ceiling operation	Limited	Unlimited	Limited	Limited/possible	Limited/possible

order to reach every point of the working space. Sometimes the working environment is very complicated, including not only high steps and deep ditches but also narrow fences and floors cluttered with debris. In this situation the robot may benefit from maximal coverage of its surface with moving tracks – therefore maximizing the so-called "Propulsion Ratio" k_{PR} described by Eq. 1.

$$k_{PR} = \frac{A_p}{A_p + A_i} \tag{1}$$

It is measured as the surface area that provides propulsion, A_p, divided by the total surface area, $A_p + A_i$, where A_i is the inert surface area of the body. To further clarify, A_p is the sum of all surface areas that could provide propulsion if in contact with the environment, while A_i is the sum of all surface areas that could not [2]. Therefore, the larger density of the propulsion means the robot should perform better. For the wheeled robots this density is limited by the maximum turning angle of the joints (wheels on the consecutive segments have to keep distance to avoid collision on curve). You can gain some improvement by mounting one wheel on the side every two segments, like in [6, 44]. Tracks provide much higher k_{PR} especially when used on each side of the segment, like in [30, 34, 35] for cuboid shape and [50] for cylindrical shape. The requirement to maximize k_{PR} has also a strong implication for the joint design – the shorter joint the smaller inert area – therefore, we can observe that robots with very short joints compared to the length of the segment [21, 34, 35] perform much better than the others [23, 30].

Most of the robots comprise of at least 4 segments, which give the ability to cross high obstacles and span large gaps, while still fitting into small openings. Sometimes segments are identical and can be easily added to or removed from the robot but usually modules have specialized functions: motor, gripping, sensory or energy storage. Some constructions have the capability of adopting different configurations to match various tasks and suit complex environments.

Most of the presented projects evolved showing transformation from purely scientific models toward application-driven and field tested construction. However, one feature that most of hypermobile robots lack is a rugged construction. Partially the reason lays in the kinematic structure consisting of many joints and therefore making mechanical construction very long and wobbly. We can find, though, two exceptions: MAKRO robot for sewer inspections [15] and Explorer used in gas pipe lines [32]. All presented robots use electric motors as a main drive and batteries as energy storage, unless they are tethered.

Regarding control system, as we could learn from the literature review, all hypermobile robots are prepared to work as teleoperators and usually autonomy is absent or very limited. In all cases, some kind of computer assistance is necessary to help human operator in difficult control of hyper articulated mobile robot but still some complex tasks like trajectory planning, obstacle overcoming, stair climbing, etc., could be performed autonomously.

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