Modular Re-Configurable Robot Drives

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***Abstract*—We propose a modular platform for wheeled mobile robots that utilises a 6-edge honey-comb prism as its basic building block to realize robot drives of diverse geometry. In terms of functionality, we designed a specific wheel suspension for a drive-module comb that can utilise both, a standard wheel or a Mecanum wheel. A quick-lock interconnection mechanism for the comb modules allows us to quickly configure/reconfigure various robot drives and enables us to realise autonomous wheeled robots with the ability to connect to other robots or even to reconfigure the robot's geometry. This configuration capability offers many interesting opportunities for robotics research since we can adapt a robot in terms of its kinematic functionality, payload and size.**

***Index Terms*—modular robots, wheeled robots, reconfigurable robots**

I. Introduction

Modular robotics represents a challenging research field that combines robotics, mechatronics, distributed control, artificial intelligence and artificial life. These robots are composed of multiple autonomous cellular modules attached to each other to form novel geometric forms. Communication among the modules and inter-module computation leads to novel functionality, for example, novel forms of locomotion and the ability for self-configuration / self-repair of the overall robot structure. Typical examples are the M-TRAN [1], [2] (cubes) and ATRON [3] (balls) modules, cube-based self-reproducing machines [4] and the tracked mobile robot of [5].

Our major focus is slightly different and more engineering oriented. We are particularly interested in building robust and adaptable wheeled mobile robots that have full awareness of their drive's kinematic capabilities. For this purpose we develop novel model-based control schemes that can operate robot drives with several wheels (possibly of different type) in an almost arbitrary geometric arrangement [6]. Furthermore, we allow on-line reconfiguration and adaption of the drives in terms of changed geometry and also changed functionality to compensate for faults, e.g. a defect steering in one wheel, during operation of the drive.

This setting might seem unusual at the first view. However, many applications and requirements can be mapped to this general control problem. For example, consider mobile robots for transport purposes. It might be desired to extract extra wheels for increased stability or traction. On the other hand, it might be of interest to build a robot that can contract its frame into a slimmer configuration so that it can pass through narrow spaces. Other applications concern multi-robot systems where the robots are either mechanically attached to each other or drive in a pre-defined formation, e.g. for collaborative transport purposes. We can view this multi-robot configuration as a single *meta robot* with complex drive geometry/functionality. And of course, we always want to achieve this functionality robustly so that faults in single or multiple wheels of the robots can be handled through operating the robot or robot cluster in a reconfigured way with possibly reduced functionality.

To demonstrate our control concepts in real-world settings we developed a modular robot platform that allows us to quickly realize robots with diverse wheel geometries and functionalities. However, the benefits of this modular robot platform should be seen in a wider context. Mobile robots are typically designed with a specific application in mind and realized as a monolithic structure with high price tag. In particular in research, one is interested in re-using the pricey hardware throughout several research projects with possibly varying objectives. As a consequence, one faces the fact that the robot platform is too generic (e.g. simple differential-drive robots) or the project aims have to be adapted in order to enable efficient re-use. Our robot platform was developed with the aspect of re-usability in mind. One can easily reconfigure and/or extend a robot through a different alignment of our basic building-block that implements a single steered/actuated wheel or an auxiliary module of the same geometric size.

Another important aspect for us is education. Hands-on experience in robotics classes is often limited to teaching students very specialised drives such as differential drives, or specialised omni-directional drives (e.g. RoboCup). Instead of limiting students to these particular drives with specific kinematics, we want to provide a tool-box for experimenting with various standard and omni-directional wheels in an almost arbitrary geometric alignment to actively study the resulting kinematics and mobility of these robots.

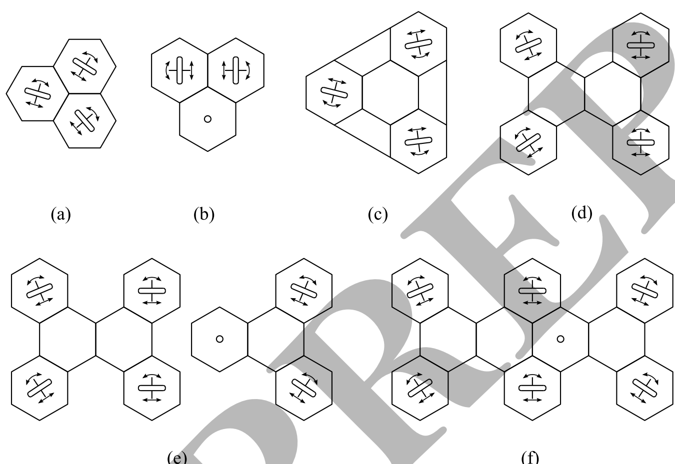
II. Modular Robot Platform at a Glance

Modularity in wheeled mobile robots is often used to reduce the price tag of a robot. Typically, one uses standardised drive-components that are attached to a particular robot frame to realize a particular robot. Examples for this approach are, for instance, the VolksBot[1] or the robot drive-components

[1] www.volksbot.de

of qfix robotics[2] for budget-type robots or [7] for industrial omnidirectional AGV. An early concept that is somehow similar to our idea was the modular robot of Mutambara [8] who uses cube-shaped modules that are attached through a specialised frame structure. We propose a similar approach where we use generic building blocks that encapsulate robot drive components. However, similar to M-TRAN/ATRON self-reconfiguration type robots, we propose to interconnect the modules directly without an auxiliary frame structure that would limit the configurability of our robot platform.

The geometric form of our choice is a *6-edge honey-comb shaped prism* that enables us to realize robot drives of diverse geometries. Fig. 1 shows some examples for drives that can be realized with our concept. Our main module, the drive module, realizes a single actuated and/or steered wheel for the robot and includes the actuators (DC motors) plus the associated servo control electronics. Besides these drive-modules, we use additional auxiliary modules of the same geometric form to (i) build the overall structure and (ii) house computing devices, additional sensors and the batteries for the robot. We can also attach passive un-steered wheels or castor wheels to the auxiliary module so that we can build a fully operational robot with less than 3 drive-modules as indicated in Fig 1b. We also use 1/2 comb-structures to (i) strengthen the overall structure, (ii) to obtain a convex overall shape of the robot (Fig. 1c) and to (iii) house batteries or sensors for the robot.



(a) (b) (c) (d)

(e) (f)

Fig. 1. Modular robot example configurations

The selected 6-edge comb geometry turns out to be optimal with respect to several aspects. Compared to other geometric forms for the prism that allows one to build fully contained structures, such as regular triangles and the often used squares (cubes), we obtain (i) a preferable size/volume ratio, and (ii) a basic geometry that allows us to realize diverse drive geometries without using too many auxiliary modules which contributes to the weight and size and, of course, the cost of an assembled robot. Furthermore, (iii), the 6-edge comb shape naturally leads to structures, where an assembly of modules is mechanically guided. This is particularly interesting whenever one realizes multi-robot systems where robots connect to each other to temporarily form larger robots (Fig. 1e-1f). Our automated interconnection mechanism is particularly shaped so that it allows automated docking of several modules as we shall introduce in more detail in Sect. III-A, Fig.4a.

Fig.2 shows an omni-directional robot that combines three drive-modules and an auxiliary module that houses the robot CPU and batteries.

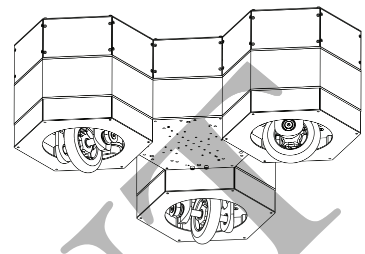
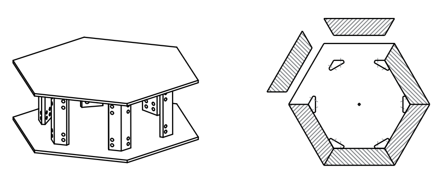


Fig. 2. Three-wheel omnidirectional robot - concept drawing

III. Comb Modules

As it can be seen in Fig. 2 we use comb-shaped prisms that consist of several layers. The middle part of a prism-shaped module represents the main mechanical structure that provides the mechanical strength for a combination of several modules. It consists of a compound of two comb-shaped plates (width 260 mm) with six prisms as stud links between them (Fig. 3a). A specifically designed alignment of the interconnecting prisms within the comb structure provides a *module-in-module* design concept for our mobile robot. Each comb-compound provides the inner (near circular) space to accommodate an actuated wheel, a CPU (e.g. in PC104 format), batteries or other robot components. Within the outer part of the comb-compound one can attach up to six modules of standardised size as shown in Fig. 3b. We mainly use the modules to encapsulate our *prism interconnection mechanism* that is used to attach prisms with each other to form the overall robot drive. However, we also use these standardised modules to encapsulate robot sensors such as ultrasonic or laser range finders.



(a) (b)

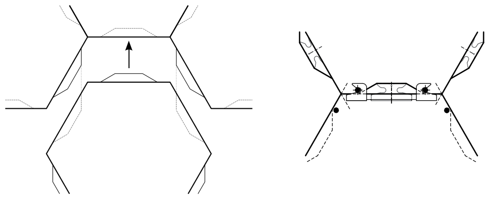
Fig. 3. Comb structure and module-in-module concept

The full comb-shaped prism will then consist of an extension of the comb-compound above and (optional) below the main mechanical structure as it can be seen in Fig. 2. This is used to encapsulate additional robot hardware, such as drive

[2]www.qfix-robotics.com

actuators and power electronics in drive modules or again CPU components in an auxiliary module.

A. Interconnection Mechanisms



(a) (b)

Fig. 4. Comb-module interconnection

In order to assemble a full robot drive out of several comb-shaped modules, we need an interconnection mechanism that attaches two comb-shaped prisms with each other and that allows us to incrementally build a compound of several modules. Another important aspect was that we want to be able to interconnect modules autonomously so that we can realize multi-robot systems that can reconfigure themselves. Fig. 4 shows the basic geometry of our interconnection mechanism and its principle realization through a self locking bolt/hook mechanism that we encapsulate in the screw-in modules for our prisms. Fig. 5 illustrates these docking modules. These docking modules can be used in an automatic mode where an additional DC motor actuates the opening/closing operation of the interconnecting hooks. However, for quick reconfigurations, we also use the same mechanism with manual activation. We also plan for an additional electric interconnection that automatically provides the power transmission to connected modules and a data-bus interconnection for data communication among the modules.

For semi-permanent structures it is also possible to use a far simpler screw-based interconnection as shown in Fig. 6. Of course, by using this connection form we reduce the robot's ability for on-line reconfiguration of the full compound, but obtain a low-cost interconnection that also reduces the weight of the overall robot drive.

B. Drive Module

The main module for our modular robot is the drive module that realizes a single steered and actuated wheel (Fig. 5). For this purpose we designed a drive unit that fits into the comb center and provides the wheel suspension with two brushless DC motors as steering and rotational actuators. Robot

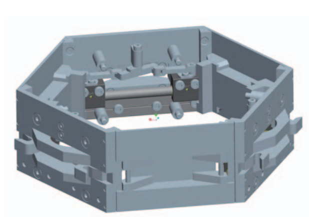


Fig. 5. Docking-modules

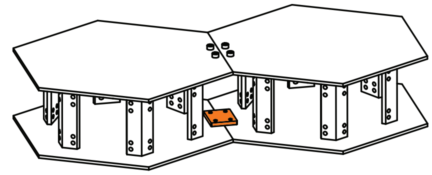
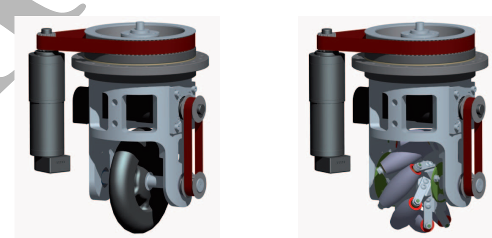


Fig. 6. Semi-permanent comb interconnection

drives with several steered standard wheels are demanding in terms of control. One has to actuate all wheels in a highly coordinated fashion so that the wheel axes define a common point of intersection that defines the movement's instantaneous center of rotation (ICR) and additionally, all wheels have to exhibit the associated compatible rotational speeds. As a consequence, we took particular care of providing a high-precision mechanism for the suspension. Similar drive units typically use an alignment where both motors are mounted onto the main drive frame and couple both movements into a turnable wheel suspension (e.g. [9]). Such a construction would, however, lead to a coupling between the steering and the wheel rotation unless one uses complex decoupling gears. We therefore decided upon a design where the DC motor for rotation actuation is directly mounted on the turning part of the wheel suspension (Fig. 7). Electric power and encoder data lines are thus coupled through slip-rings.



(a) (b)

Fig. 7. Drive unit with standard and omni-directional wheel

Mounting the drive actuator onto the wheel suspension was also easily possible since we decided upon a rather untypical design. We designed our drive units to be as generic as possible. In order to realize a wide spectrum of robot drives we designed the wheel suspension to utilise both, standard wheels and omni-directional Mecanum wheels (Fig. 7). The latter actually does not require a steerable construction, but having a turnable suspension allows us to quickly configure diverse robot drives through the steering actuator or simply manually whenever we use a drive unit without this actuator. As a consequence, we decided upon a wider wheel suspension that is machined out of an aluminium tube of appropriate diameter. Another benefit of this design was that we were able to use a standard industrial slewing ring bearing to obtain the turnable interconnection to the comb-compound with appropriate strength and alignment precision.

Fig. 8 shows the combination of the basic comb compound with the drive unit and its associated power electronics. The

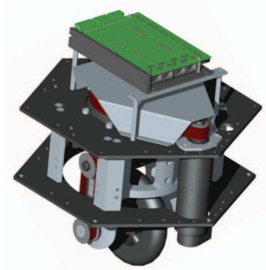


Fig. 8. Drive module core components

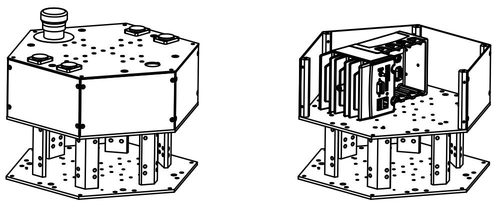


Fig. 9. Auxiliary (CPU) module

drive belt mechanism for the steering actuation and the power electronics / servo control units are enclosed in the top part of the comb-shaped prism. Whereas a bottom extension of the prism is used to prevent damages to the wheel's drive-belt mechanism and the vertically mounted steering motor. Revisit Fig. 5 for the concept drawing of the resulting 3-layered comb-shaped prism for the drive unit.

C. Auxiliary Module

To realize the diverse drive geometries as indicated in Fig. 1 we need additional modules of the comb-shaped prism geometry that we introduced for the drive modules above. The additional modules are typically built in terms of the core comb-compound (Fig. 3) with the top extension to enclose additional robot components such as the drive's/robot's main CPU, batteries or even sensors. Fig. 9 shows our CPU module where the top extension is used to enclose a National Instruments compact RIO real-time CPU. We use the space within the comb-compound for the drive's batteries (not shown).

We also use the auxiliary modules to mount additional supporting wheels without steering/actuation so that we can realize robots with less than three drive modules (Fig. 10 and Fig. 1b).

Sometimes it is advisable to build a robot drive with convex shape. As a consequence, we also provide 1/2 size modules as shown in Fig. 1c. These modules can further increase the strength of the drive compound. Because we attach these modules at the outside of a drive compound it is also interesting to use these modules for the robot's batteries, since we can easily attach/detach these modules.

IV. Control Architecture

Our aim is to provide a versatile modular platform for research and education in robot mobility, kinematics and control. As a consequence, we put particular emphasis to furnish drive modules with appropriate mechanical- and control-precision.

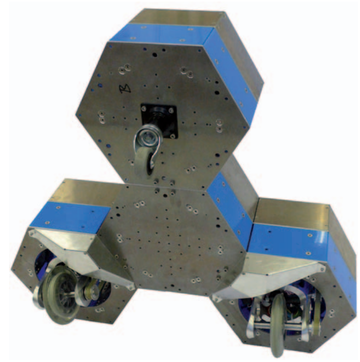


Fig. 10. Example Robot

Power considerations, that directly correspond to achievable accelerations for the steering and rotational actuation in our drive module are also key to build highly reactive and precise robot drives.

Robot drives with several steered and actuated standard wheels represent in almost all configuration cases a mechanically over-determined system. For example, take the 3-wheel omnidirectional configuration shown in Fig. 1c. A desired robot movement that defines longitudinal velocities ($\dot{x}$ and $\dot{y}$) or equivalently the location of the ICR (x_{ICR}, y_{ICR}) together with the angular velocity ($\dot{\Theta}$) of the robot, defines six dependent variables (three steering angles β_i so that all wheel axes meet in the ICR and the associated three wheel velocities ω_i) through the inverse kinematics of the drive. Agile movements of the robot demand a prompt shift of the ICR. The kinematics require a coordinated actuation at all times, thus also throughout the ICR shift. This dictates a highly coordinated actuation of the wheels' actuators - a challenging nonlinear constrained control problem. As a consequence, we put particular emphasis onto the low-level kinematics/robot control hardware. We divide the control hardware into high-precision servo-controllers for each drive module and a real-time CPU that serves as a central coordinated control unit. Communication between the CPU and the servo-controllers in the drive-modules is done through a high speed CAN network. The real-time CPU of our choice is a National

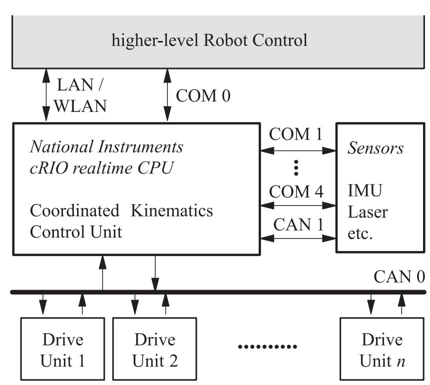


Fig. 11. Control architecture

Instruments compact RIO (cRIO) system. The cRIO's modular architecture nicely complements our modular robot platform concept. Our comb-modules can accommodate the standard 4-module cRIO or the newly available single-board cRIO. In our preferred configuration we only use 3 out of the 4 cRIO modules for: (i) one high-speed CAN module that provides two CAN ports, (ii) a serial communication module that provides 4 RS232/RS485 ports and (iii) a wireless LAN/LAN-switch module for robot communication. With this configuration we can realize a control architecture as shown in Fig. 11 where one CAN port is used for the drive-unit communication, 4 serial ports can be used to communicate with sensors (in our case a MicroStrain 3DM IMU sensor and a Hokuyo URG laser scanner), the WLAN/LAN-switch module provides connectivity with other on-robot CPUs and a base-station or other robots within the WLAN network. We can also use the standard serial port of the cRIO real-time controller or the second CAN network for communication with other robot CPUs that realize, for example, higher-level control tasks such as path and task planning and/or vision. Another advantage of the selected cRIO system is that we use the system's on-board 3 MGate FPGA to directly realize highly time-critical control tasks.

However, we designed our modular robot system, in particular the size of the comb-shaped prism module so that we can also utilise on-board computers in the PC104 format or even computers in the larger Mini-ITX form factor.

V. Aspects in Research and Education

As introduced above, we particularly designed our modular robot platform for an ongoing research project in model-based fault-tolerant and reconfigurable control for wheeled robots. However, our platform opened several other opportunities for research and education. A detailed description of the individual endeavours would go beyond the scope of this paper, nevertheless, we want to give a concise overview of ongoing work with our modular robot platform:

A. Research

1) Kinematics Reasoning and Coordinated Control: We are developing a generic control unit for wheeled mobile robots. Unless the usual approach, where the mobility of the drive is designed in a task-oriented way leading to a specific drive geometry and functionality, we use a generic *model programmed* approach. In detail, we specify the particular robot drive in terms of its geometry and functionality (steered, un-steered standard wheel, Mecanum wheel, etc.) and provide a kinematics solver for the control system that automatically deduces the inverse kinematics for the drive that is used within the controller [10], [6]. Furthermore, this kinematic reasoning functionality automatically provides the necessary insight in a drive's mobility so that a controller can check the feasibility of a drive command that it receives from a higher-level path planner. This insight in the drive's kinematics is also useful for the coordinated control task that computes the required set-points for the individual drives (steering angles and rotational speeds) that ensures the existence of a unique ICR for all time points during operation.

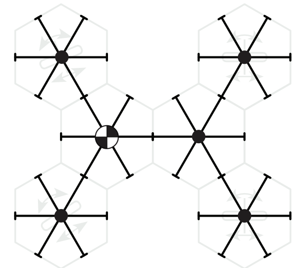


Fig. 12. Graph representation of a 4-wheel robot

2) Fault Detection, Diagnosis and Reconfiguration: Robot drives represent a complex mechatronic system that relies on the correct operation of all components. A robust control and automation system requires constant system-monitoring and estimation to provide the current mode of operation and state estimates for control. Furthermore, one has to detect any deviation from nominal operational conditions and instantly localise (diagnose) for possible faults in the drive. Powerful sensor fusion and diagnosis algorithms are key for this functionality [11]. However, a high computational complexity of this multi-mode estimation process requires efficient algorithms for on-board monitoring in real-time. We are currently developing new algorithms for a mixed continuous/discrete (i.e. hybrid) estimation and diagnosis [12] that will enable us to use this sophisticated estimation and diagnosis tool for on-line health monitoring and control within our robot drives.

3) Self (Re-)Configuration of Modular Robots: Currently, we operate our robot system with a central CPU and drive modules that locally implement low-level servo control. However, our ability to re-configure a comb compound using our sophisticated interconnection mechanism opens the way for multi-robot systems that autonomously change their overall structure. An autonomous interconnection of two robots would represent the simplest form of this functionality. However, we can also think of robots that join, operate cooperatively, and separate again into a different configuration. Such a functionality will require an automated mechanical and electrical interconnection between modules and a distribution of the computational resources throughout the system, e.g. one CPU for every drive module. We are currently developing algorithms for automated and distributed configuration management. For example, we compute the overall geometry of a given configuration through distributed graph-based algorithms. Fig. 12 shows such a graph for a 4-wheel robot that we use (currently off-line) to automatically deduce the drive model, in particular the geometric alignment, for kinematics reasoning and coordinated control that we mentioned above.

4) Networked Control: Our modular robot system uses networks for interconnecting the individual drive modules. The demanding and time-critical control task of coordinated control over a communication network raises research-relevant questions in networked control. In particular, when moving from a centralised single-robot solution to coordinated multi-robot systems or even the fully distributed form where coordinated drive-control is done locally at each drive module. We are currently starting to explore these aspects that will be key for building highly reconfigurable mobile robot systems.

B. Robotics Education

The ability to quickly realize a diverse set of mobile robots is particularly helpful for our advanced robotics courses. Hands on experiences with mobile robots are typically limited to few specialised robots that are used for ongoing research projects. These robots are either very generic, e.g. the versatile MobileRobots[3] Pioneer robots that, however, utilise un-steered wheels in a differential drive mode. Other options, in particular for omni-directional robot drives arise whenever RoboCup soccer robots are available. All of these robots, however, cover very specific mobility/kinematics aspects only. With our modular system, however, we can configure the classic differential drive and ackermann steering robot drives and various omni-directional robot drives. We can also configure un-typical drives (e.g. drives with Mecanum- and standard-wheels etc.) that allows students to actively evaluate various drive concepts and thus understand mobility and kinematics aspects of mobile robots in more detail.

The modular system means also that a given robot platform can be easily extended. For example one can start with a simple robot that utilises a single steered wheel and two additional un-steered/un-actuated wheels, i.e. one drive module and two auxiliary modules with one un-steered wheel each. Later on, one can easily extend the set of modules to include additional drive modules, Mecanum wheels, etc. to realize an omni-directional robot or even a fleet of simple robots - depending on the needs in education and research. Our module-in-module design provides also increased re-usability for sensors. Again, one could start with cheap ultrasonic sensors for obstacle detection and extend the sensor-module set with a more expensive laser rangefinder later on. Thus, the ability for simple reconfiguration allows one to utilise existing set of hardware modules (drive modules, auxiliary modules, sensor modules, etc.) in various, task-specific configurations.

VI. Conclusion

We presented a novel modular robot system that allows us to realize wheeled robots of diverse geometry and functionality. To build robot drives in a frame-less LEGO-like way, we proposed to use a 6-edge honey-comb shaped prism as the basic building block. A comb module is used to accommodate either the robot CPU and its sensors, or as for the core module for our drive, a single actuated wheel. The interconnection between comb modules is achieved through a special quick-lock mechanism or semi-permanently through a screw mechanism. Additionally, we designed the comb prism to accommodate either the quick-lock interconnection mechanism or, alternatively, sensor modules (e.g. ultrasonic or laser range-finders, bumpers, etc.). The drive modules accommodate a versatile wheel suspension that realizes a steered and actuated wheel and the associated high-precision servo control electronics. We can equip the wheel suspension either with a standard wheel or optionally with a Mecanum wheel. This overall configuration-flexibility together with the diverse geometric configurability due to the 6-edge comb structure allows us to realize a wide range of possible robot drives, both in terms of geometry but also in terms of functionality.

Acknowledgment

This research has been funded by the Austrian Science Fund (FWF) under grant P20041-N15.

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