LAURON V: A Versatile Six-Legged Walking Robot with Advanced Maneuverability

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LAURON V: A Versatile Six-Legged Walking Robot with Advanced Maneuverability

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***Abstract*— Adaptive multi-legged walking robots are predestined to be applied in rough and hazardous terrain. Their walking and climbing skills allow them to operate at places that are unreachable for most wheeled vehicles. In this paper, we present the design and development of the new six-legged walking robot LAURON V with its improved kinematics and robust mechanical structure. Each leg has four independent joints that enable LAURON to cope with steep inclines, large obstacles and makes it possible to manipulate objects with its front legs. Autonomy, robustness and a large payload capacity together with its impressive terrain adaptability make LAURON V highly suitable for all kinds of field applications.**

I. INTRODUCTION

Walking robots, especially hexapods, are designed to walk in difficult, rough and often unknown terrain. Stable locomotion in such an environment, however, is not easy and therefore many researcher around the world continuously develop new concepts to improve a variety of legged robots.

The FZI Research Center for Information Technology has a long standing tradition of walking robots [1], [2]. In particular the LAURON hexapods [3], [4], [5], [6] reach back over 20 years. With each iteration this biologically inspired hexapod was made more robust, learned new skills and continued to extend the previous research results. Of course, there are other walking robots that show advanced walking skills like HyQ [7] or LS3 [8]. Many six-legged walking robots apply the predominant yaw-pitch-pitch kinematics, which is based on the typical insect-like leg design with three joints: Messor II [9], AMOS-WD06[10], BILL-Stick[11], DLR Crawler [12] and Anton [13]. The impressive number of 18 degrees of freedom (DoF) offers a good flexibility and walking abilities on mainly flat terrain with obstacles. However, if the terrain becomes more challenging, as it is the case with larger obstacles or steep slopes, this kinematic design reaches its limit as the orientation of the feet cannot be chosen freely. Some of these limitations are addressed by sophisticated motion planning methods and foothold selection approaches [14],[15],[16]. But of course, these approaches require detailed environmental information and an exact robot localization. Certainly, there are also many multi-legged walking robots with an advanced leg design (more than three degrees of freedom per leg): CR200 [17], Athlete [18], LEMUR [19] and CREX [20]. Their additional degrees of freedom (DoF) are mostly designed for special tasks like object manipulation and are rarely used to improve their climbing or walking skills. For example, object manipulation with legged robots has been demonstrated by Boston Dynamics' BigDog [21] and by six-legged robots like CREX [20] or LEMUR [19]. In spite of the continuous improvement of LAURON IVc we reached the limits of its kinematic design and hardware, provoking development of LAURON V. The main design objectives were the kinematic improvements, enabling LAURON V to walk over steeper inclines and larger obstacles as well as to enable manipulation tasks. Some parts, like the main body have been redesigned while proven mechanical designs were sustained. With minor changes, the behavior-based control was adapted to the new hardware, allowing LAURON V to inherit all of LAURON IVc's capabilities. A new high power computer system, a modular sensor setup and an enhanced electronics structure complete the redesign, improving its autonomy. LAURON V's size, mechatronic robustness, payload capacity and maneuverability make it absolutely unique and address the requirements of challenging field missions like search and rescue operations as well as inspection, exploration and surveillance tasks (see Fig. 1).

Fig. 1: Walking Robot LAURON V in the Field.

Section 2 of this work will present a short history and the design objectives for LAURON V. Section 3 and 4 focus on kinematics and mechanical design. The hierarchical control architecture will be described in Section 5. LAURON V's advanced skills and the evaluation at the EU Taranis 2013 are content of the Sections 6 and 7. Finally, Section 8 will conclude our work and give a short outlook to future work.

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II. LAURON HISTORY AND DESIGN OBJECTIVES

In the last 20 years, LAURON was able to successfully demonstrate its robustness, walking skills in rough terrain and high degree of autonomy. Like all LAURON generations, the new kinematic design was inspired by the stick insect Carausius morosus. Especially, the kinematics of the leg (see Fig. 2) and the optimized leg configuration (mounting angles and positions) show strong similarities to this insect. Although, the insect-like kinematics of LAURON I to IV allowed these robots to walk in rough and difficult environments, their three joints per leg limited the maneuverability and terrain adaptability. For example, when walking up steep inclines, stairs or large obstacles, LAURON quickly reached its kinematic limits and encountered difficulties to provide the huge torques that were required in the alpha joints.

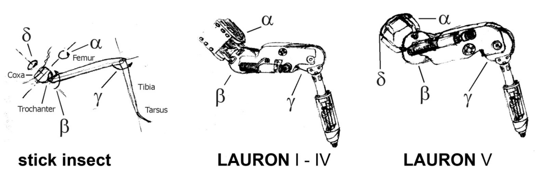

Fig. 2: LAURON's Leg Evolution

The main design objectives for LAURON V were to improve the robots climbing capabilities by reducing these alpha torques, preserve the achieved mechanical robustness and enable the robot to perform complex manipulation tasks with its front legs. Much effort was put in LAURON's autonomy. But the developed high-level planning, environment mapping and localization as well as mission control components are not in the scope of this paper. Nevertheless, some of these skills can be seen at http://youtu.be/m8MXGFzjJxs.

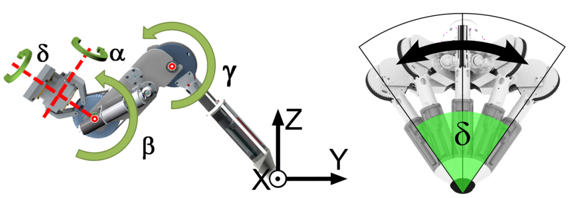

Fig. 3: Enhanced leg kinematics: ability to set the foot orientation while remaining at the same foot tip position.

III. KINEMATIC DESIGN

The biggest kinematic enhancement of LAURON V is its increased maneuverability and adaptability due to the additional fourth rotational delta joint in each leg (see left part of Fig. 3). With this additional joint, which was constructed in a very compact way (more details in [22]), LAURON V is able to set one additional angle thus change the orientation of the foot tip towards the ground and therefore influence the load distribution within the leg (see right part of Fig. 3). It is now possible to reduce the critical amount of alpha torque that used to stress these joints while walking on a steep inclines before[30]. The ability to influence the orientation angle towards the ground also offers great potential for further improvements (energy, stability, velocity) when walking mainly on flat terrain.

A. Leg Configuration

The leg configuration was optimized by interpreting an extensive Yoshikawa workspace analysis [23], [24]. The resulting absolutely unique mounting angles show similarities to the leg configuration angles of the stick insect [25].

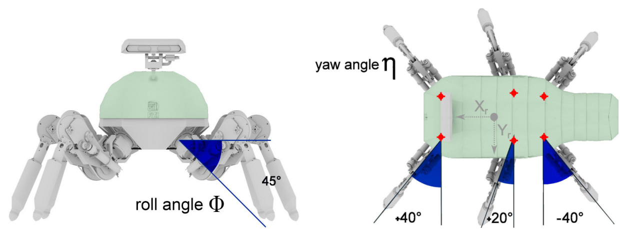

Fig. 4: LAURON V optimized leg configuration

The leg mounting positions (see Tab. I) were carefully selected in accordance with the biological counterpart [25] and with the goal to increase the forelegs' workspace and to shift the center of mass (CoM) to the rear. The kinematic design of LAURON V can be understood as a combination of an optimized as well as bio-inspired design approach.

	foreleg	middle leg	hind leg
Φ-Angle	+45°	+45°	+45°
η-Angle	+40°	+20°	-40°
X-Position	+228.4 mm	−67.3 mm	−203.4 mm
Y-Position	±80.7 mm	±96.2 mm	±80.7 mm
Z-Position	−56.2 mm	−56.2 mm	−56.2 mm

TABLE I: LAURON V - Leg Configuration

B. Inverse Kinematics

A previous, simple version of LAURON V's inverse kinematics (IK) focused on creating an orthogonal orientation of the leg's foot tip towards the ground. The new vector-based solution enables us to set one additional angle for each foot tip and thus control the orientation of the leg within the possible workspace. The developed IK allows us to separately control the orientation of each leg and to set the orientations of all legs in a collaborative way. The proposed solution is defined in the leg's coordinate system (LCS), thus enabling us to use the same kinematics for all legs.

The joint's axes are labeled as A, B, C, D for the δ, α, β and γ joint (see Fig. 5). The LCS's origin is placed in the leg's α joint (B). The Z-axis of LCS is denoted by $\mathbf{Z_{LCS}}$. To set a consistent orientation independently of the legs' mounting angles, LAURON's body fixed Z_r-axis is used as reference and is denoted by the vector $\mathbf{Z_r} = (r_x, r_y, r_z)$. The desired working point position of the foot tip is denoted by $W = (w_x, w_x, w_z)$. All leg parts from the alpha joint to the foot tip lie in the same plane E. The leg orientation angle

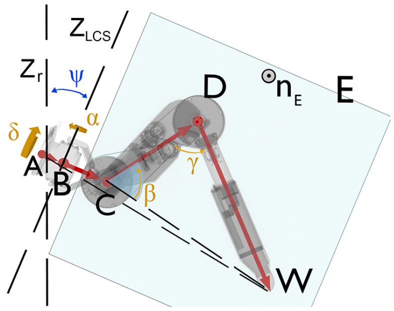

Fig. 5: Points A, B, C, D are placed in the joint axes.

ψ is the angle between the vector $\mathbf{Z_r}$ and plane E (in X_r direction).

First, the proposed algorithm determines the parameters of the plane E represented by the four parameters: P_a, P_b, P_c, P_d. They are used in the plane equation:

$$P_a x + P_b y + P_c z + P_d = 0. \tag{1}$$

Equation (1) is satisfied by every point (x, y, z) that lies on the plane. The normal vector of the plane $\mathbf{n_E}$ is defined by (P_a, P_b, P_c). The IK makes use of the desired foot tip position W and desired leg orientation ψ to find the corresponding joint angles. The computations begin with solving a system of equations to find the parameters of E, that satisfy the imposed constraints:

$$P_a 0 + P_b 0 + P_c 0 + P_d = 0 \tag{2a}$$
$$P_a w_x + P_b w_y + P_c w_z + P_d = 0 \tag{2b}$$
$$P_a r_x + P_b r_y + P_c r_z = cos(\frac{\pi}{2} - \psi) \tag{2c}$$
$$P_a^2 + P_b^2 + P_c^2 = 1 \tag{2d}$$

The first constraint is represented by (2a) and stems from the fact, that the origin of the LCS must lie in the plane E and therefore satisfies (1). The equation (1) must also be satisfied by the desired foot point W, which is formulated in (2b). Equation (2c) is imposed by the desired ψ angle. If the angle between the plane E and the vector $\mathbf{Z_r}$ is equal to ψ, then the angle between the normal vector of the plane $\mathbf{n_E}$ and vector $\mathbf{Z_r}$ is equal to the $\psi - \frac{\pi}{2}$. Equation (2d) is the normalization constraint of the normal of the plane $\mathbf{n_E}$.

Only one of the two solutions is valid due to the definition of the direction of the positive angle ψ.

With knowledge of the plane E, the individual joint angles can be computed. The δ angle is calculated as the angle between leg plane E and the vector $\mathbf{Z_{LCS}}$. The computation is performed using the normal vector of the plane $\mathbf{n_E}$. From Fig. 5 it might appear that the normal vector of the plane $\mathbf{n_E}$ should be rotated by $-\alpha$ about the vector $\mathbf{Z_{LCS}}$ prior to δ calculation, but this operation is omitted as the angle between two arbitrary real-valued vectors remain constant if the rotations are performed about these vectors. The α angle is computed as the angle between vectors $\overrightarrow{BC}$ and $\overrightarrow{AB}$, whereas β angle is the angle between vectors $\overrightarrow{CD}$ and $\overrightarrow{BC}$. The remaining γ angle is equal to the angle between vectors $\overrightarrow{DW}$ and $\overrightarrow{CD}$. Concluding, the IK problem can be solved with the following equations:

$$\delta = \frac{\pi}{2} - \arccos(\mathbf{Z_{lcs}} \cdot \mathbf{n_E}) \tag{3a}$$
$$\alpha = \arccos(\overrightarrow{BC} \cdot \overrightarrow{AB}) \tag{3b}$$
$$\beta = \arccos(\overrightarrow{CD} \cdot \overrightarrow{BC}) \tag{3c}$$
$$\gamma = \arccos(\overrightarrow{DW} \cdot \overrightarrow{CD}) \tag{3d}$$

The analytical form of the proposed solution is not computationally demanding and can be calculated fast. This new inverse kinematics has been successfully tested on LAURON V and significantly expands LAURON's climbing skills on slopes.

IV. Mechanical Design

Within the last nine years LAURON IVc's mechanical leg design proved to be reliable and robust. This design was adapted and improved for better maintenance [22]. In contrast to its ancestors LAURON V's main body is now made of an inner-skeleton like structure. The basic shape of this structure follows a design concept, that was evaluated in a very early stage of development.In this phase, we also decided to develop an abdomen for the control PC in the rear of the robot. It additionally shifts the CoM to the rear, making it easier to manipulate with its front legs and creates a natural look. A light-weight plastic casing/skin and strong 3D-printed shells on the bottom protect all internal parts.

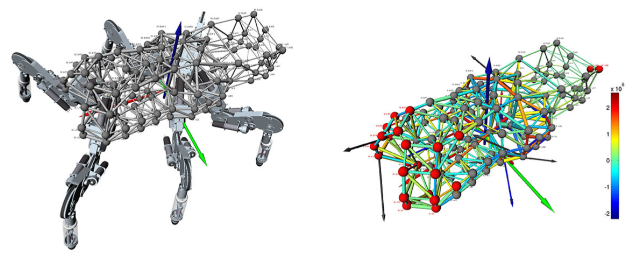

Fig. 6: Structure Optimization of Inner-Skeleton

The inner structure is the result of an iterative wire-frame optimization routine. The thickness of each element was optimized to endure the stress induced during the walking process. Finally, the complex wire-frame structure (see Fig. 6) was refined to the simplified, inner-skeleton frame made of high-strength aluminum as shown in Fig. 7.

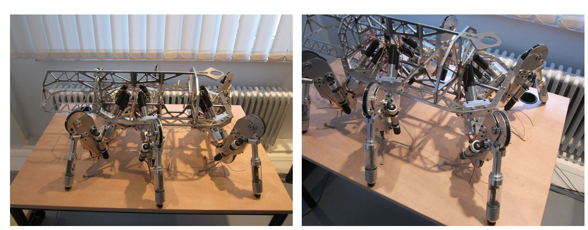

Fig. 7: Inner-Skeleton made from High-Strength Aluminum

After first experiments and endurance tests some mechanical improvements have been carried out. The inner-skeleton has proven to be extremely robust, and was therefore partially redesigned to reduce weight. Besides, the gear belts of the beta joints, which carry the largest amount of the robot's weight, have been replaced by more reliable steel chains.

A. Technical Specifications

The most important technical specifications that characterize LAURON V are summarized in Table II.

LAURON V	
Type	Legged Walking Robot
No. of Legs	6
No. of Joints per Leg	4 (delta, alpha, beta, gamma)
No. of Head Joints	2 (pan & tilt)
Total DOF (active)	26
Compliance	Spring damper in each foot (6 passive DOF)
Size [footprint]	0.9m x 0.8m
Height [min - max]	0.61m - 0.84m (form ground to PTU head)
Weight	40kg (+2kg for batteries)
Max Payload	10kg
Power Supply	$>$ 2 hours with 2 x 22.2V 8Ah (LiPo)
Power Consumption	Standing: 100W, Walking 150W
On-board PC	Intel Core i7 4x3.0 GHz with 8GB RAM
Modular Sensors	IR-Camera, Stereo-Camera, RGB-D, Velodyne HDL-32E, Rotating Hokuyo

TABLE II: LAURON V - Specifications

V. Control Design

A modular, behavior-based design approach allows us to subdivide this system into understandable hierarchical layers and small individual behaviors.

A. Hardware Architecture

LAURON's on-board PC with its Intel Core i7 CPU offers sufficient computational power to run all software, the behavior-based control system and the hardware abstraction layer, on the robot. The low-level PID-Joint-Controllers run on 9 custom motor controller boards (UCoM - Universal Controller Modules [26]) that are connected to the control PC via CAN bus interface. The control center, including a 3D model of the robot and all relevant control interfaces, is executed on an independent external PC. More details on the control hardware of LAURON V can be found in Fig. 8.

B. HAL - Hardware Abstraction Layer

LAURON's hardware abstraction layer is used to filter data, multiplex and convert values (e.g. sensor ticks to gradient angles) and solve the direct and inverse kinematics. For example, the HAL adds the robot specific offsets to the IMU raw values and transforms them to the correct robot frame. All motor currents are normalized and scaled with a non-linear function [27] and the ground contact values are filtered by a combination of mean and median filters. Compared to

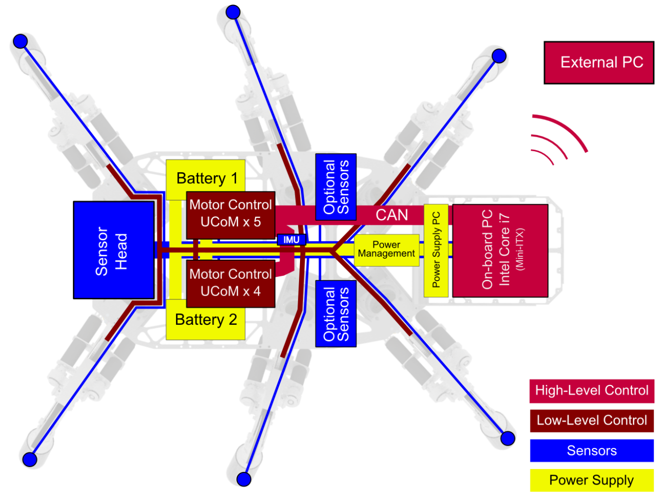

Fig. 8: LAURON V Control Hardware Architecture

other components, the calculation of the inverse kinematics (see Section III) is a rather complex part in the HAL. By placing HAL between behavior-based control system and the low-level motor controllers, the control systems remains largely robot independent. By following this design principle it was easy to transfer the control system from LAURON IVc to LAURON V. In fact, we were able to quickly reuse the behavior-based control by adapting the HAL to the characteristics of LAURON V within a few hours.

C. Behavior-Based Control System

In the last years, LAURON has successfully been controlled by a behavior-based control systems [28]. A generalized system architecture with the most important behaviors can be seen in Fig. 9. The desired velocities (x, y, α) and the walking patterns (tri-, tetra-, pentapod and free gait) are given as external inputs. This input can either come directly from the control center or from higher software components (path planning, mission control, etc.). Foot point generating behaviors calculate the AEP (Anterior Extreme Position), PEP (Posterior Extreme Position), swing height and the resulting step cycle. Gait behaviors motivate the swing or stance behavior of each leg and coordinate the legs to generate the desired patterns. Behavior fusions are responsible for a smooth transitions and intelligent combination of all values. For example: the step size (AEP and PEP) and step frequency are only increased by a small delta each walking step until the desired overall robot velocity has been reached. Parameters from these behaviors and motivation signals are used in the local leg behavior groups to generate the leg and body movements. Each independent local leg behavior group consists of a swing, stance and reflex behaviors (collision detection and ground contact). The swing and stance behavior are motivated by the walking pattern behaviors. The reflexes are directly motivated by the swing and stance behaviors and then triggered by sensor data (i.e. currents or ground contacts). The posture behaviors generate shifts and offsets to control the body's inclination, height and position. All these behaviors combine their outputs to a position (X, Y, Z) and orientation angle (ψ) for each leg. The IK within the HAL determines all corresponding joint angles, the UCoMs control the motors and read all internal sensor values.

This modular architecture and its abstract control scheme enable LAURON to walk over unknown terrain without intensive planning or human intervention. It can easily be extended by further behaviors and modified by replacing individual behaviors, which has lead to a continuous growth and refinement of LAURON's control system.

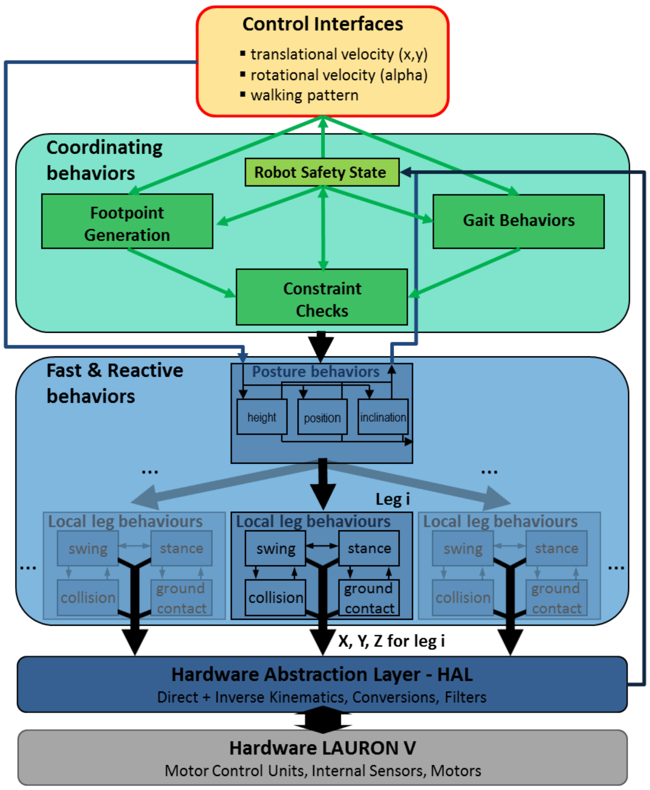

Fig. 9: Behavior-based control system of LAURON V

VI. Advanced Skills

The new leg kinematics and the special mounting increase LAURON's overall performance, but also enable completely novel skills that extend its capabilities.

A. Increased Maneuverability

Steep slopes have been a challenge for LAURON IVc as very high torques are needed in these situations. With the additional joint, LAURON V is able to align its legs parallel to the gravity vector, reducing the stress on the legs significantly (see Fig. 10). This joint is actively used by reactive posture behaviors, which then improves LAURON's performance to keep its body balanced and walk up steep slopes or over large obstacles. Now, LAURON V is able to autonomously walk up slopes with an inclination larger than 25.0 degrees and remained stable until 42.8 degree [30].

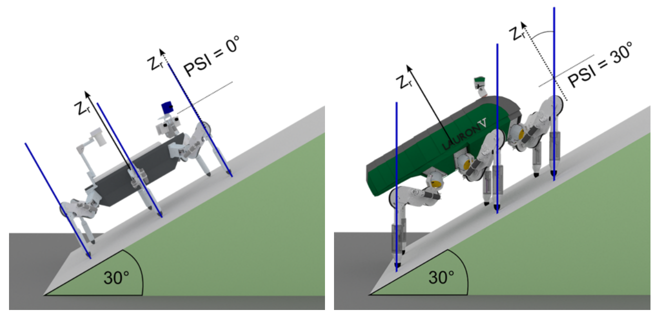

Fig. 10: Increased maneuverability on steep slopes: (left) LAURON IVc is not able to orientate its legs, (right) LAURON V with PSI angle control - leg orientation (IK + posture control) decreases torques and increases stability.

B. Dual and Single Leg Manipulation

By shifting the center of mass towards the rear, LAURON can stand on its 4 hind legs, leaving the 2 front legs free for manipulation tasks. In contrast to LAURON IVc the new leg kinematics can reach targets from various angles and lift objects with both legs. A new fully retractable gripper makes LAURON capable of single leg manipulation, where grasped objects can be stored on its back (see Fig. 11). Making use of the legs as manipulators saves the weight of an additional robotic arm. A video showing LAURON's successful grasp with a single leg can be seen at: http://youtu.be/m8MXGFzjJxs.

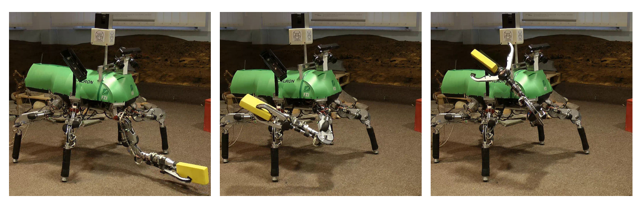

Fig. 11: LAURON uses its front leg with a light-weight gripper to pick up objects and store them on its back.

VII. Field Experiments

As part of the robotic exhibition, LAURON V was first presented to the public during the IEEE ICRA 2013 in Karlsruhe, Germany. Shortly afterwards, LAURON took part in the EU Taranis Field Exercise in Salzburg, Austria.

A. Modular Sensor Setup

The on-board motherboard offers a variety of standard interfaces (USB 3.0/2.0, LAN, RS232, WLAN) which are extended by a CAN interface card. A flexible mounting system, together with a 24V and 12V supply voltage, make it easy to quickly change the sensors mounted to the pan-tilt head or the back. Due to its great payload capacity (see Table II) large sensors like the Velodyne HDL-32E can be carried with hardly any effects on the robot. LAURON's modular sensor setup and its superior walking abilities make it a versatile multi-purpose research platform suitable for a great number of hazardous and challenging applications.

B. Evaluation at Taranis Field Exercise

Fig. 12: Search and Rescue Tasks at Chemical Accident Site Golling during the EU Taranis Field Exercise, Austria.

The EU Taranis Field Exercise took place at different exercise sites all located around the city of Salzburg, Austria [29]. Almost 1000 international rescue workers from various organizations trained and demonstrated their skills during this large scale field exercise. LAURON V was part of the *SAR Robots* team of the Bavarian Red Cross. It supported a search and rescue operation at the Chemical Accident Site Golling (see Fig. 12). Its infrared camera gave valuable information to the rescue workers and supported them in finding buried casualties after the ceiling of a building had collapsed. Compared to search and rescue dogs, LAURON can be applied for a longer time and can also provide sensor data (live videos, pictures, 3D maps of environments, etc.). Nevertheless, LAURON's climbing and walking skills still need further improvements to match the capabilities of a professional search and rescue dog. There were no special, technical arrangements to support any robots at this exercise. The primary goal was to create a realistic exercise for the human rescue workers. Nevertheless, LAURON V performed quite well in this real world scenario and demonstrated that its autonomy, robustness and flexibility make walking robots valuable for search and rescue missions.

VIII. Conclusions and Future Works

In this work we presented the design, development and evaluation of the fifth LAURON walking robot generation. Similar to its ancestors, the kinematics and control system were inspired by the stick insect. The new leg design, together with the optimized leg configuration enable LAURON to cope with difficult obstacles and steep inclines. Due to the increased workspace of the legs and the ability to orientate its feet freely, LAURON V can be used for complex mobile manipulation tasks. Real field applications have demonstrated that its robust mechatronics fulfill the requirements of demanding search and rescue missions in the wake of natural disasters. In the future, we will extend LAURON's walking range by applying energy efficient locomotion strategies and further increase the system's autonomy by enhancing its planning and mission control components as well as its reactive behaviors [30].

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