# Task-Specific Synthesis and Design of a mobile six-DoF Hexa Parallel Robot for Weed Control

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**Abstract.** In automated weed control, kinematics of varying complexity are required for tool guidance, depending on the weeding principle. Mechanical tools in particular require several degrees of freedom (DoF) in order to operate in a plant-specific way, which can be realized by parallel kinematic machines due to their dynamic performance. The development of a kinematic structure under task-specific requirements is done using combined structural and dimensional synthesis and a detailed manual design stage, which leads to a new variant of the six-DoF Hexa robot.

**Keywords:** SDG6 · SDG11 · SDG12 · Hexa parallel robot · weed control

## 1 Introduction and State of the Art

For most crops in agriculture weed control effort is required due to the competition for biological resources. Still the most widely used approach is applying herbicides, which are economical but come with downsides, as they are usually non-selective and partly inefficient. Herbicides and their degradation products can even infiltrate unintended areas as water bodies, which should be avoided with respect to negative effects on human and animal health. Using automated robotic systems is a promising alternative since manual weeding is expensive. In this paper, we are focusing on the kinematic aspect of robotics for tool handling rather than on the topic of mobile robots e.g. carrying the weeding tools, as shown in Fig 1. In the following, we refer to this as parallel kinematic machine (PKM).

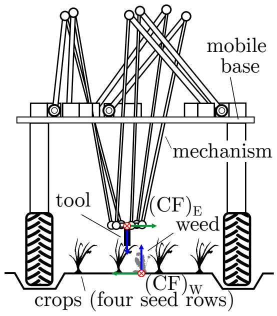



**Fig. 1.** Simplified scheme of the presented weeding system (rear view)

Weeding robots can be categorized according to the operating principle of the weeding tool (mechanical, chemical, electric discharge, laser irradiation, water jet treatment), and accordingly different requirements exist for tool handling.

In numerous applications, the movement of the carrier system is used, so no further kinematics is required for tool positioning. The "Ecorobotix ARA" [1] uses a large array of individually controllable nozzles to fine-dose herbicides, a similar principle is applied in [2]. There are also systems for weed removal by laser irradiation, as in the "Carbon Robotics LaserWeeder" [3], which works without an additional tool positioning. [4] shows more examples of mechanical weeding, both with rotating tools, and completely passive.

Selective weeding using mechanical tools requires at least one degree of freedom (DoF) for tool positioning. "Bonirob", a multifunctional mobile agriculture robot introduced in [5] was used for weeding with fixed nozzles and additional linear actuated stamps. Other systems with one-DoF tool positioning include the "Naio Technologies OZ" [6] with various tools, the "Carre Aggriculture Anatis" [3] and the "Farmdroid" [7], both with one-DoF digging tools. In the Farming Revolution "Farming GT" [8] the rotating tool is guided by two-DoF serial kinematics. Further applications with mechanical tools, lasers or water jets can be found in [4], containing only serial kinematics.

Systems with tool handling kinematics of three or more DoF can be used for single-plant-based application. Providing high dynamics and a proven design, Delta robots are used in several weeding systems for tool handling, e.g. in the prototype of "Small Robot Company" [9] with a linear Delta and an electrode, and by Ecorobotix [1] with Delta robots for positioning nozzles in an earlier version. Serial kinematics, as in the SwagBot [10], where a six-DoF robotic arm positions a nozzle, are barely represented and not promising for an efficient application. In [11] a six-DoF parallel robot, the Hexa introduced in [12], was used, but primarily for positioning the camera system rather than the weeding tool. Further applications for all types of tool handling can be found in the reviews [4,13,14].

Unlike the references above, we pursue the idea of a six-DoF parallel robot which is able to provide *spatial orientation* of the *rotating tool* prototype to be tested, which opens more possibilities for weed control. This is similar to industrial machining tasks, where the task DoF can be termed as 3T2R, i.e. three translations and two rotations are defined. The crucial part of the development of such a weeding robot is the kinematic synthesis. *Combined structural and dimensional synthesis* is a suitable method for this purpose especially for parallel robots, introduced in [15] also at the example of a Hexa robot and does not suffer from the restriction to very few proven common structures. Using this method, we present the development of parallel robot with the following *contributions*:

- the transfer of technical requirements for a given weeding process into an optimization problem within the combined synthesis framework,
- the development of a six-DoF parallel robot prototype for weeding application, which is a new realization of the Hexa robot by its assembly mode and dimensioning.
- By optimizing the redundant coordinate ($\varphi_z$) already in the synthesis we can realize structures despite a high risk of self collision.

The paper is outlined as follows. The task requirements are collected in Sec. 2 and translated to a synthesis framework in Sec. 3. The design is discussed in Sec. 4 followed by a workspace evaluation in Sec. 5.

## 2 Application and Requirements

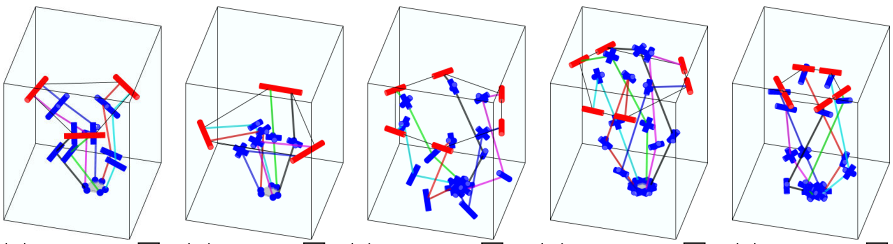
Our focus is on the organic cultivation of onion crops, as their profitability suffers particularly from weeds. The crops are seeded in flat beds, grouped in four evenly spaced rows between the tractor driving lanes as sketched in Fig. 1. The single-plant-based weeding aims at a narrow band of 60 mm around the seed rows (*intra-row*), since this is most vulnerable and more rough methods are used at more distant areas, referred to as *inter-row* methods. The overall system consist of a mobile robot carrying a PKM and a camera system. Image recognition and stereo vision is used to locate the crops and weeds. The developed robot has to guide the rotating milling tool to the desired coordinates based on camera images. For accessibility and promising advantages in treatment, full tilting of the tool is required (3T2R task), since the tool's rotation axis needs no additional actuation. Further requirements have to be taken into account within the synthesis:

- min. workspace in $y$-direction $\pm 190$ mm (including vehicle deviation)
- min. workspace in vertical direction of 340 mm (jumping crops possible)
- installation space: two parallel robots are placed next to each other (in $y$-direction) with centers 1000 mm apart from each other, which is the distance of the outer seed rows. Reduced by a safety distance of 100 mm. No vertical limit
- driving speed of vehicle ($1\,\mathrm{km\,h^{-1}}$) and a density of four plants per meter, which has to be provided by the acceleration and speed of the end effector
- min. diameter of mobile platform due to the tool mounting of 42 mm
- the total mass of the mounted milling spindle of 1.5 kg has to be carried
- min. tilt angle of the mobile platform: 15° (accessibility of the plant roots)
- mobile platform DoF: 3T3R (unrestricted research on weeding process, redundant DoF can be used to optimize trajectories and avoiding singularities)
- position accuracy: 0.5 mm

In the following, these requirements are translated into the synthesis framework.

## 3 Synthesis

The robot's structural and dimensional synthesis is performed based on the idea of [15] using a general implementation, briefly summarized in [16] with remarks the aspect of functional redundancy, relevant for 3T2R tasks. It provides several possible structures with specified kinematic parameters and uses a multi-objective particle swarm optimization with parallel computation of the structures on a computing cluster. A kinematics and dynamics model is used to simulate a given reference trajectory. In order to consider the requirements in synthesis, these must be mathematically formulated within the fitness function. Requirements are ensured by the hierarchical constraints and the objective functions to be minimized, as well as by the choice of the underlying reference trajectory. During the synthesis, the 13–16 *optimization variables* of feasible



**(a)** 6-RRRS □ **(b)** 6-RUS ▽ **(c)** 6-RURU △ **(d)** 6-RUUR ✳ **(e)** 6-RRUU +

**Fig. 2.** Visualizations of kinematic structures considered within synthesis, taken from the results in Fig. 3 with installation space represented by cuboids (sidelengths of 0.9 m)

structures are varied, consisting of the serial leg's kinematic parameters and further geometric dimensions (base position and radius, platform radius).

The *reference trajectory* has to represent the workspace requirements, therefore it is composed of target positions at the edge of the workspace and random tilt angles of the tool within the specified range. With regard to the *constraints*, kinematics-derived criteria such as solvable inverse kinematics (IK), joint limits, self collisions and installation space are examined as well as dynamics-derived criteria like force and material stress limits. The constraints of the optimization parameters were chosen on the basis of the task so wide that the optimization is not unnecessarily limited by them. Only static forces are considered within the synthesis, since specific dynamics of the trajectory is not defined at this stage of development. A total platform payload of 2 kg is assumed next to the size-dependent link and platform mass, based on an aluminum alloy tube or plate geometry to optimize for good force transmission. Within the *objective function* the two minimization criteria drive torque and speed are defined, since these are dominant for the overall system's cost. The optimization of the tool rotation, resulting from the 3T2R task's functional redundancy, is performed as an inner loop within the synthesis, as described in [16]. The *set of structures* is reduced by the presumption that linear drives are excluded due to higher vulnerability to vibrations and dirt. Further, five-DoF (3T2R) structures are prone to tolerance-induced clamping due to overconstraints and are mostly based on prismatic joints, therefore not considered. Thus, six-DoF PKM with revolute actuation at the base remain. Due to technical realization and higher robustness against collisions, only structures with three or four joints are regarded. The remaining structures are various implementations of 6-RRRS, 6-RUS, 6-RURU, 6-RUUR and 6-RRUU-structures, following the terminology in [17] and shown in Fig. 2.

This approach does not fully represent special circumstances of a real construction in detail. Thus, the development process is structured as an iterative procedure in which findings from the constructive design are fed back into subsequent synthesis runs. The set of structures, parameter limits and collision bodies are therefore successively adjusted, which is described in Sec. 4 and results in our final solution shown in Fig. 4, representing a 6-RUS variant. Other kinematic

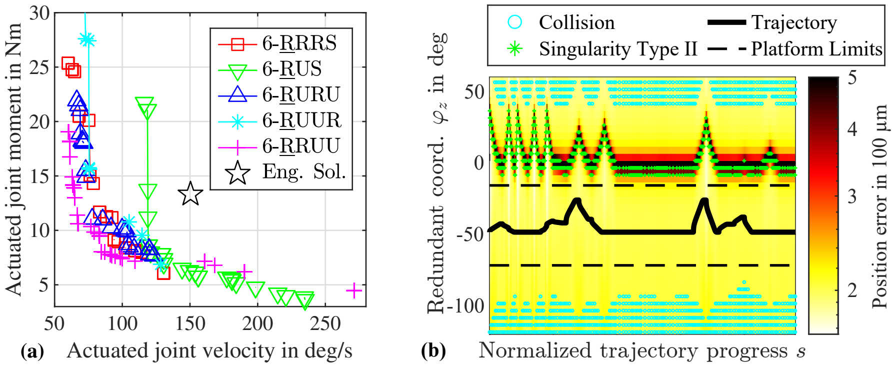



**Fig. 3.** Pareto front (a) and performance map of trajectory (b)

structures did not match the requirements in these further synthesis iterations and were discarded due to the complex technical realization.

The optimization was rerun for the initial settings to rank our final solution. Figure 3 (a) shows the pareto-optimal particles for the considered structures, as well as our engineered solution. The engineering solution is outperformed by the RUS solutions which are *theoretically* possible. However, several points must be noted. After the design selection based on the synthesis version of [16], the optimization of the redundant coordinate within the trajectory IK was improved by using dynamic programming (DP) instead of acceleration-level nullspace projection as shown in [18], thus avoiding oscillations which lead to high dynamic forces in simulation. Furthermore, the marked solution was affected by real conditions which does not apply to all other markers with simplified conditions: our engineering solution is based on the DP trajectory within the platform rotation limits $-70° \leq \varphi_z \leq -29°$, since this is the range where no limits of the real spherical joints are exceeded (see Sec. 4). The specific joint implementation could not yet be considered within the synthesis framework. Further, additional collision bodies of the motors were used for the design. This may explain the non-optimality of the engineering solutions against the RUS markers. Thus, only a qualitative proposition can be taken from the figure at this stage of development.

Based on our solution, Fig. 3 (b) visualizes the result of DP along the reference trajectory from synthesis in a heatmap of the position error, which is shown for variation of the platform rotation $\varphi_z$. The error is based on the assumption of a joint angle resolution of $7''$ by the textbook method from [17]. Therefore, it can not be quantitatively transferred to our prototype and only covers the aspect of encoder accuracy. The qualitative plot shows that a wide range of platform rotations with homogenous performance is achieved by the chosen design. Invalid areas due to collisions and singularities are marked, as well as the mentioned platform limits. It can be seen that the trajectory regards the limits in this post-processing, so the solution's reliability is sufficient.

## 4 Design

In order to analyse various synthesis solutions, the design process takes place in iterations, as introduced before. Thus, complex structures can be eliminated based on their design effort or manufacturing costs. Furthermore, the angular ranges of passive joints can be calculated and the necessary design effort can be estimated using design catalogues (see e.g. [19]), to evaluate the realization with standard components. The tilting angle range of common *universal joints* are around 30°–45°, while *spherical joints* are more restricted within 12°–30°. The rotation angle of spherical joints is not limited, therefore the joint alignment is critical in terms of end-effector movement, although this is not yet explicitly considered within the synthesis framework. The synthesis is based on predefined requirements, therefore the results can be seen as functional structure [20]. Design methods, like a morphological box were used to find suitable realizations.

Starting from the drive, the universal joint is connected by an inclined crank (Fig. 4 (a)). The obtained assembly configuration (elbows inside) results in an acute angle between the links, leading to particular requirements for the universal joints as shown in Fig. 4 (b). The following lower connection rod links the universal joint via a spherical joint to the end-effector platform (Fig. 4 (c)). Representing a particular Hexa variant, the proposed PKM is one of the few realized structures where the larger part of the kinematic chain moves above and below the horizontal plane of the base frame. The angled arrangement of the cranks, seen in Fig. 4 (d), and the elbow-inside assembly mode differs from the known Hexa-robot. Both features are not found in existing $\underline{R}$US-structures, which mainly operate in configurations with elbows located below the base and pointing outwards like in [21].

The advantage of this variant compared to existing structures is due to the dominating restriction of the installation space, so a relatively compact design can be achieved within a given workspace requirement (see Sec. 5). As a result of the kinematic chains crossing the base plane, in combination with elbows mounted inside, an open plate concept has been developed. Based on the application, the drives are mounted on top of a *multi-part base plate*, to protect them from contamination of the weed control process. Furthermore, the mounting of the actuators could be simplified by the fact, that their weight rests on the plate. As for the *guiding rods*, aluminum tubes have been selected based on their mechanical properties, relatively low weight and costs. Due to the minimum angle in the *elbows* of 38°, commercially available joints could not be used. Thus, custom joints have been developed on basis of [22] with adaptions to limit manufacturing cost and adjust angular range. Based on the reference trajectory, the mounting orientation of the *spherical joints* is analyzed by determining the minimal angular range to validate whether cost-efficient standard joints (e.g. rod end bearings, Fig. 4 (c)) can be used. Otherwise, the structure could only be realized with custom designed joints. As a result the spherical joints are parallel to the designed planes on the side of the platform. Furthermore, the aluminium end-effector platform (strength 25 mm) has been designed for minimum cost. To estimate the rough performance required for the rotational drives, the inertia properties

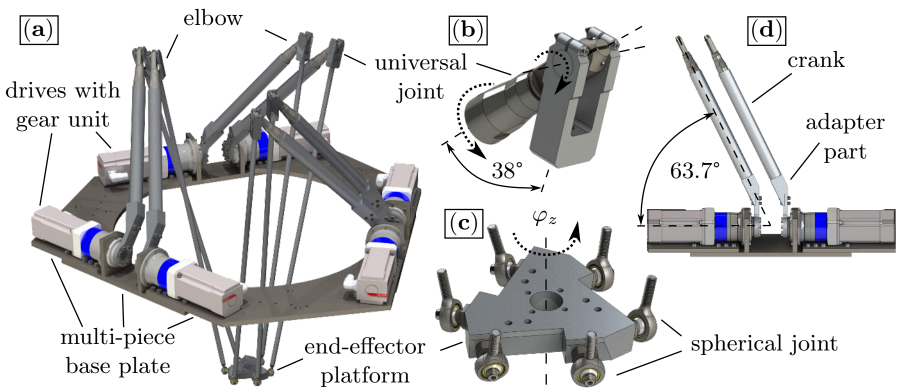



**Fig. 4.** Overview of the proposed parallel robot (CAD rendering) (a), *universal joint*s (b), end-effector platform (c), inclined crank (d)

of the entire robot were determined using the CAD-model and the dynamics calculation was rerun in order to size the drives more precisely. Permanent-magnet synchronous motors (nominal values: $M_{\mathrm{N}} = 2.40\,\mathrm{N\,m}$, $n_{\mathrm{N}} = 2500\,\mathrm{min}^{-1}$) in combination with planetary gears ($i = 50$, $M_{\max} = 50\,\mathrm{N\,m}$ ) have been selected, since direct drives are typically more expensive. In order to classify these values according to Fig. 3 (a), the max. joint moment is determined without gear-friction to $M_{\max} = 50\,\mathrm{N\,m}$ and the max. joint velocity calculated to $v_{\max} = 300\,^{\circ}\,\mathrm{s}^{-1}$, resulting in a safety factor of approximately 2 for the velocity and 3 for the drive torque. The moment requirements resulting from synthesis should be achieved with a higher safety factor as the velocity, because the individual masses are partly under-represented in the synthesis calculation, resulting in fewer loads. Furthermore, the geometry of the guiding rods were determined by the internal forces repeatedly calculated for adjusted inertia properties in the synthesis. The realization results in a moving mass of approximately 16 kg excluding the tool. The maximum static payload is restricted by the selected motor-gearbox combination and is calculated to $m_{\max} = 8\,\mathrm{kg}$ with respect to the workspace within the relevant installation space.

## 5 Workspace Characteristics

Given the final design, further evaluations of *workspace characteristics* are provided, which are out the scope of the dimensional synthesis in Sec. 3 due to their high computational effort. Still, the workspace is important for the application since the reference trajectory does not guarantee a gapless workspace. In addition to the kinematic limits themselves, the workspace also suffers from truncation due to inherent collision, installation space and joint angle limits, where the spherical joint's tilt angles are dominant. The workspace is calculated specifying a fixed platform tilting angle (by using $\varphi_x$ and $\varphi_y$ from intrinsic $X$-

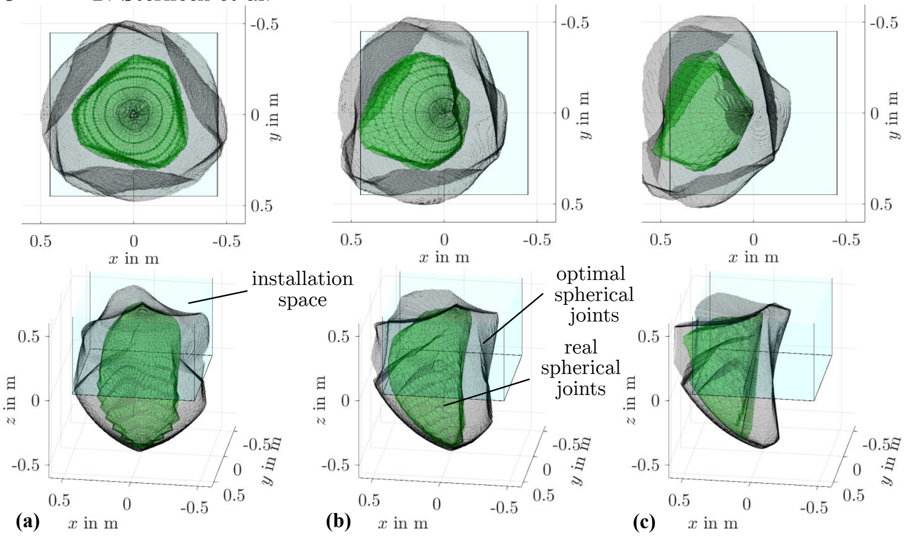



**Fig. 5.** Workspace of the proposed parallel robot with platform tilt angle of 0° (a), −10° (b), −20° (c)

$Y$-$Z$ Cardan angles). Any rotation $\varphi_z$ around the tool axis is allowed (subject to other constraints), as this represents the redundant coordinate. Therefore, the computed workspace volumes correspond to the constant-orientation workspace regarding the reduced orientation of the 3T2R task, cf. [17]. The platform tilt angle is set to 0°, −10° and −20° using $\varphi_y$, visualized in Fig.5. First, leaving aside the mentioned design-related limitations and only assuming a tilt angle limit of 29° (considered the best case of a real rod end bearing), the workspace with a total volume between $0.522\,\mathrm{m}^3$ ($\varphi_y = 0°$) and $0.389\,\mathrm{m}^3$ ($\varphi_y = -20°$) can be seen in Fig. 5 (volumes colored gray), as this gives an undistorted view of the characteristics of the actual kinematic structure. Due to the requirements of the weed control process and the derived reference trajectory, a relatively large workspace can be obtained. The workspace decreases especially in the radius and shifts laterally in $x$-direction, with increasing platform orientation. In relation to the sketched installation space, which is defined upwards starting at $z = 0$, the workspace fills a high proportion of the volume. Structures determined in the synthesis are not allowed to exceed this limitation, because this plane represents the ground. Taking the restrictions of the installed spherical joints into account, the resulting workspace volumes are presented in the figure as well (volumes colored green). The remaining volume amounts $0.205\,\mathrm{m}^3$ ($\varphi_y = 0°$) and $0.125\,\mathrm{m}^3$ ($\varphi_y = -20°$). Although there is a loss of volume in the peripheral area (radial direction), this meets the requirements of the weed control process. Therefore the kinematic is suitable for the intended purpose.

## 6 Conclusion

The synthesis and design of a six-DoF parallel robot was presented in this paper, with a variety of structures being tested. As a result a particularly compact variant of the well-known HEXA robot was implemented. Task redundancy was already considered within synthesis and using this, the effective avoidance of singularities has been demonstrated. The workspace characteristics examined are suitable for the intended weeding application.

## Acknowledgement

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