Group project for the course of

Mechanical Design for Mechatronics

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Technical report
TITOLO

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February 28, 2022

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1 Product design specification

The goal of our project is to create our implementation of the *CyberOrto* [1] made by *Mindshub*, an non-lucrative association based in Ala (Trentino). The goal of this robot is to automatically handle an amateur vegetable garden by performing this 3 principle actions:

i) planting the seeds of the desired plant in a location decided by the user using a web interface;

ii) constantly provide water to the vegetable;

iii) extirpate undesired plants.

By talking with the association that worked (and is still improving) on the product we acknowledged the following requirements (mainly related to the functionality of the product) that the structure has to satisfy:

i) the arm appendix must suits an interface that allows to have an interchangeable set of tools (like the one use to plow the terrain);

ii) the arm appendix should accommodate a small pipe in order to irrigate the vegetables; in particular this has to be connected to an external reservoir (with no dimension specified if it's position is fixed) or by using an internal reservoir on the moving structure of at least $4l$ (that can periodically be refilled) if it's not possible to directly attach the arm to the main reservoir;

iii) the minimum accepted working area of the robot is a rectangle of dimension $4m \times 3m$; the robot should be design keeping in mind the possibility to increase the working area by expanding it over one edge (for example having the possibility to work on a $8m \times 3m$ terrain);

iv) the structure can house the electronic control unit of the robot that's remotely connected to the server using wireless connection and by doing so should accommodate a battery the allows the robot to work for at least $4h$. The power consumption of the structure should be minimized if possible (at the actual state the prototype consumes $40W$ and has a battery of $240Wh$ weighting $6.3kg$);

v) regarding the accuracy of the movement of the system the allowed backlash on the working point should always be less then $1cm$ with the control technique implemented and the goal is to have maximum $5mm$ of deviation from the nominal value;

vi) the structure should be mainly composed of standard components and should be as cheap as possible in order to make it affordable for everyone.

Loads and operating conditions   The structure should be able to perform all it's operation while being safe and fully functional. For the design and the verification of the structure the loads related to wind can be neglected due to the presence of an anemometer that's mounted on the robot and ensures that the robot works only on a sufficiently safe environment.

The heavier operation performed by the robot is the extirpation that's done by plowing the soil with a rotating element **AGGIUNGERE UNA BREVE DESCRIZIONE**. Considering the actual mounted motor to perform this operation the torque that has to be transmitted to the plower is of $T_{\text{plower}} = 0.8N \cdot m$.

1.1 Requirements & specifications

With the promise being said it's possible to express the main requirements, associated to the aim dictated by our customer and our design rules, and the specifications of the designed machine. All this information, collected in table 1, has to be considered in each step of the design phase in order to develop the mechanical solution.

While developing the project other factors should be kept in mind:

- the possibility to pack all the necessary components in a *small* transportation box (the box shouldn't present and edge greater than $2m$, maximum sum of all the edges less then $3m$) in order to avoid shipping issues;

- the kit should be feasible to all private enthusiast that enjoy *do-it-yourself* projects and this has to kept in mind; mounting tools should be the most common ones (screwdrivers, Allen keys...); welding finishes are not recommended.

2 Concept generation

With all the premise that lead the development of the project, the first thing that has to be done is generate the concept that can later be compared to choose the best design solution that can become a concrete realization of the ideas.

Kinematic configurations The first key operation that the robot has to perform is reaching a desired point on the working space and so, in planar kinematics, the machine should present two degrees of freedom that allow to reach all the possible positions; this can be done considering 3 main joint configuration that allows to perform such operations:

- double prismatic joints (figure 1.a) where two perpendicular linear guides can be used to move on the plane;

- prismatic and revolute joint (figure 1.b) where the arm that's free to rotate it's mounted on top of a linear guide. This kind of kinematic chain is currently used by the MindsHub concept;

- double revolute joints (figure 1.c), typical configuration of a robot arm, that constraint the framing point to be fixed.

By a first analysis the third configuration (double revolute joint) isn't feasible for the project due to the fact that the system presents a fixed pivot point respect to the frame and to work more area it's mandatory to increase the length of the edges (and this is an issue for the *extendibility* of the machine).

1) Geometry:

    1.1) dimension of the terrain to cultive — at least $4m \times 3m$, extendible if possible

    1.2) vertical clearance from the ground of the robot while moving — $\geq 50cm$

2) Kinematic:

    2.1) time travel between further points in the field — $\leq 10s$

    2.2) accuracy of the working appendix respect to nominal value — max $\pm 1cm$, target $\pm 5mm$

3) Energy:

    3.1) low energy consumption — max 40W, target 20W

    3.2) in-device battery with docking station — battery $\geq 240Wh$ or 4+ hour of work

4) Functionalities:

    4.1a) provide direct water access to irrigate the soil

    4.1b) or provide a reservoir that can be automatically refilled on a docking station — $\geq 4l$

    4.2) standard mount on the appendix arm that can fit multiple working tools

    4.3) plowing the terrain — $T_{\text{plower,max}} = 0.8N \cdot m$

    4.4) provide a pneumatic circuit used for the appendix that plants seeds

5) Materials:

    5.1) components standardization — very high

    5.2) materials should be weather proof (oxidation free)

6) Terms of use:

    6.1) easy to assemble — max 2 persons required

    6.2) fatigue resistance — infinite life-cycles if possible, min 10^6

    6.3) insensible to environmental conditions (weather and dirt)

7) Loading conditions:

    7.1) wind and environmental actions can be neglected with robot in action

8) Costs: — $\leq €2\,000$
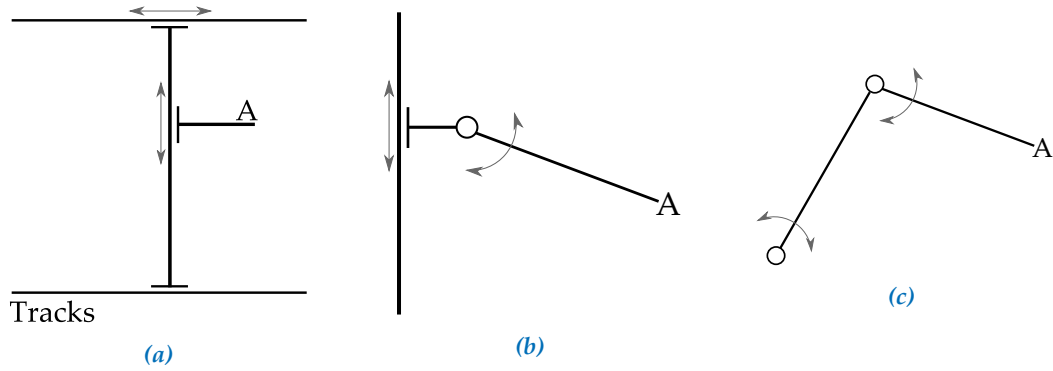
Figure 1: main kinematics coupling that allows to univocally determine the position of a point A in a plane: (a) double prismatic joints, (b) prismatic and revolute joint, (c) double revolute joints.

Concept #1 The first concept (figure 2) is realised with a double prismatic joint. In particular point A and A' lies on parallel tracks placed on the ground that can be extended in order to increase the cultivated area. The working arm can move along an elevated beam connecting the track (point B) and can move vertically to cultivate point P.
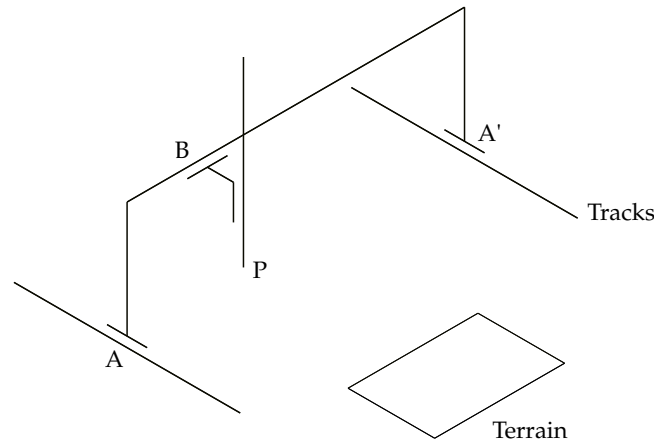

Figure 2: concept #1 realised with double prismatic joint.

This structure present a frame for the arm that's stable while operating due to it's arch structure; possible problem to this implementation is that long elevated beam (subjected to the loads of the arms and it's mass) can deflect and fail statically. Also, if possible, rotoidal coupling should be used (and for this we can refer to concept #2).

Concept #2 The second concept (figure 3) is similar to the first one but one prismatic joint is replaced with a revolute connection put in the middle of the elevated beam. The length of the edge BP from a top view must be equal to half the length of the supporting bar in order to reach all points in the rectangular space.

This structure also presents the pro of concept #1 of having a stable frame structure for the operating arm due to it's arch conformation and, as addition, uses a revolute joint to control the second degree of freedom of the arm. However this implementation increases the mechanical load on the elevated beam (increasing the torsion due to the higher arm of the actions on the tool tip respect to the elevated bar).

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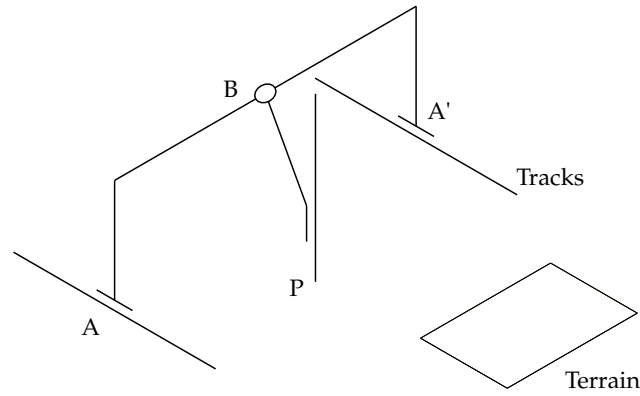
Figure 3: concept #2 realised with a combination of both prismatic and revolute joint.

Concept #3 The third concept (figure 4) is similar to #2 but instead of using two parallel tracks, the prismatic joint uses only one of them.
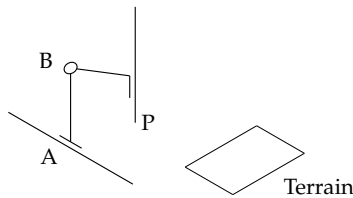
Figure 4: concept #3 realised with a combination of both prismatic and revolute joint.

This implementation avoid the problem of high deflection of concepts #1 and #2 by removing the long elevated framing beam, but also increases the reactional momentum that the prismatic joint *A* should bear in order to maintain stable the system.

2.1 Decision matrix

With a brief overview of the 3 main concept generated, the unbiased choice can be performed by constructing and evaluating the decision matrix (table 2). The main objective evaluated are:

- costs: based on the estimated material cost considering quantity and types of parts that can be used for the implementation;

- reliability: expected mechanical resistance of the structure subjected to nominal loads as well as unexpected external loads (such environment of customer that interact with the structure);

- lifetime: expected lifetime of the product based on fatigue considerations;

- adaptability: criteria that evaluates how easy is to modify geometrical parameters to meet specific custom requirement of the final customer based on asperity and tolerances of the terrain to cultivate;

- team experience: based on the overall design feasibility made by the team.

With the decision matrix completed the chosen concept is the first on which the motion is performed only by prismatic joints.

Table 2: *decision matrix.*

Objective	Weight	Parameter	Concept #1			Concept #2			Concept #3		
			Mag	Score	Value	Mag	Score	Value	Mag	Score	Value
Material costs	0.2	relative €	medium	7	1.4	high	5	1	low	9	1.8
Reliability	0.3	experience	good	8	2.4	okay	6	1.8	poor-fair	3	0.9
Lifetime	0.15	experience	great	10	1.5	good	8	1.2	fair	4	0.6
Adaptability	0.2	experience	good	8	1.6	okay-good	7	1.4	fair	4	0.8
Team experience	0.15	experience	good	8	1.2	great	10	1.5	fair	4	0.6
Overall score:					**8.1**			6.9			4.7

Qualitative score assignments: poor = 2, fair = 4, okay = 6, good = 8, great = 10.

2.2 Material selection

The main structural components are beams that, for client requirements, should be standard and so for this reason T slot extruded aluminium profiles (figure 5) are chosen after the following considerations:

- better volume-to-price ratio and lower density (respect to inox steels), so reducing costs associated to the spare parts and shipping;

- availability in the marker: there are a lot of vendors that provide profiles with various geometrical dimensions, different aluminium alloy and surface finishes. This spare parts can be easily accessed by every private costumer;

- for T slot extruded profiles lots of auxiliary components (such supporting brackets, fasteners, hinges...) are provided from the same profiles manufacturers, reducing the need of custom made part and so decreasing the costs.

This elements can be also purchased with an anodized finish that allows to improve the corrosion resistance and so increasing the expected life time of the product in uncontrolled outdoor environment.
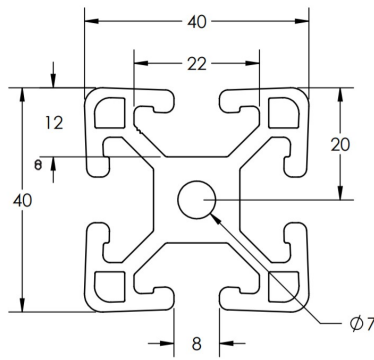
Figure 5: technical drawing of a T-slot profile's cross-section. The particular sketch represent the model TS40-40LM *by Tslots [2].*

Mechanical properties For the design part the following mechanical properties are considered: ultimate tensile strength $\sigma_{uts} = 260 MPa$, yielding strength $\sigma_{ys} = 240 MPa$, Young's module $E = 70 GPa$, Poisson's ratio $\nu = 0.32$; this are mean value and full material designation can be found on table A.1.1 (page 11).
For the final verification more detailed mechanical properties are going to be used depending on the final profile selection.

3 Preliminary design

Based on the selected concept the simplest body diagram has been created in order to start the dimensioning of the main elements of the structure. Considering the possible practical implementation of the system, the symbolic representation of the moving frame has been made (figure 6).

The design involves a main elevated track (body 2) supported by two vertical supporting beams (body 1 and 3); the connection between body 1 and 2 has done by a full joint with 6 degrees of constrain while the connection of the track with the other
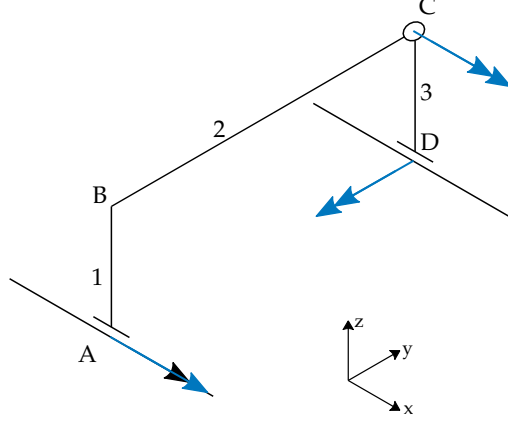
Figure 6: schematic representation of the moving frame supporting the arm; blue arrows are describes the rotational degree of freedom left by the joints.

support is done by a hinge that leaves free the rotation over the global x axis. The two vertical supports can slide on two parallel tracks and the associated prismatic joints constraints 4 degrees of freedom each, leaving the system free to slide and accommodating rotation over the global x axis. The choice of the joints is made in order to make the system immune to misalignment of the tracks (in particular considering their non-perfect parallelism and the fact that they can't be coplanar).

As simplification on both the geometry and the load we consider:

- on the elevated track the loads transferred by the working appendix are modelled as a pure vertical force P (mainly related to the approximate weight) and a torque T that model's the one due to the plower; the eccentricities of both forces are in this case neglected and the application of application of both actions is placed at a distance ξ refered to the local coordinate z_2 of the elevated track;

- the vertical supports are equally dimensioned and present a characteristic height H; the elevated track connecting them has length L;

- referring to figure **RIFERIMENTO FIGURA**, the action associated to the joint in B aren't described (the theoretical connection of bodies 1 and 2 should behave as a single element), however the practical final result will imply the connection of two separate beams.

Chosen the two hyper-static variable X_1, X_2 to reduce the problem to an isostatic one the parametric definitions of the reaction forces are

$$R_{Az} = \frac{L - \xi}{L} P \qquad M_{Ay} = -X_2 \qquad R_{Cz} = \frac{\xi}{L} P \qquad M_{Cy} = X_2$$

$$M_{Cz} = T - X_1 \qquad R_{Dz} = \frac{\xi}{L} P \qquad M_{Dz} = T - X_1$$

The other actions ($R_{Ay}, R_{Cx}, R_{Cy}, R_{Dy}$) are instead identically null. To solve the hyperstatic problem the Castigliano's theorem has been used, computing the elastic energy U_e of the structure neglecting shear loads:

$$U_e = \sum_{i=1}^{3} \int_0^{L_i} \left(\frac{N_i^2}{2EA_i} + \frac{M_{x,i}^2}{2EI_{xx,i}} + \frac{M_{y,i}^2}{2EI_{yy,i}} + \frac{M_{z,i}^2}{2GJ_{t,i}} \right) dz$$

Table 3: *selected beams section chosen from the Parker IPS catalogue [4] and related main properties (area, moments of inertia and weight per unit length).*

Usage	Area $A[cm^2]$	Moments of inertia $I_{xx}[cm^4]$	$I_{yy}[cm^4]$	Weight $p[kg/m]$	Product code
track	9.29	14.26	14.26	2.53	11-040
supports	5.20	8.27	8.27	1.41	10-540
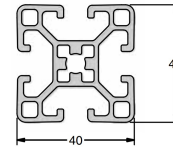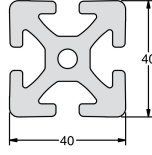
Representation of the sections for the track beam (on the left) and the supports (right).

Assuming the generalized displacement related to the hyper-static variables as null, solving the equations $\partial U_e/\partial X_1 = 0$ and $\partial U_e/\partial X_2$ determines the solutions

$$X_1 = \frac{T}{2} \qquad\qquad X_2 = 0$$

In this preliminary design phase in order to over-estimate the loads the the frame should bear a weight $P = 196N$ is considered (associated to a weight of about $20kg$ that relates to all the carried equipment on the moving arm including batteries and water tank) and a value of torque $T = 0.8N \cdot m$ associated to the maximum force due to the plower that's transmitted on the frame itself. As geometrical dimension the considered length of the rail is $L = 3m$ supported to a height $H = 0.7m$.

Choice of the standard beams With the preliminary design model described, different solutions can be found looking from various vendors present in the marker. In particular for the project main reference has been made to the Parker IPS catalogue [4] due to the high availability of accessories components, however similar product can be found by other vendors (as group we also evaluated 8020 [5] and Tslots by Bonnel Aluminum [2]).

Data-sheets presents information about the section area A and second moments of area I_{xx}, I_{yy} respect the primary axes, however no information is given for the torsional rigidity J_t and so the related component is in the calculation neglected. Considering the lack in the consideration of both shear and torsion and the imprecise geometry and load conditions, the chosen product must withstand the mentioned load with a safety-factor ϕ of at least 6.

After an iterative process, the standard section in table 3 are chosen withstanding a minimum safety factor $\phi = 9.12$ considering only axial and bending loads.

4 Design process and verifications

With the data obtained from the preliminary analysis, the design has been carried using the 3D CAD software `AutoDesk Inventor Professional` and using theory from the course, static verification of highly stressed components and joints have been performed.

A   Appendix

A.1   Materials

Table A.1.1: *list of available aluminium alloys for T slot profiles with relative mechanical properties (based on* `ASTM B-221` *standard) and extruded profile vendor that provides this results.*

ASTM code	$\sigma_{uts}[MPa]$	$\sigma_{ys}[MPa]$	$E[GPa]$	$\nu[\cdot]$	usage	vendors
6005-T5	262	241	70	0.33	profiles	Parker
6105-T5	262	241	70	0.33	profiles	80/20, Parker
6061-T6	262	241	70	0.33	accessories	Parker
6063-T6	206	172	70	0.32	profiles, accessories	Parker
6065-T6	206	172	68	0.32	profiles	tslots

Parameters of the table: σ_{uts} ultimate tensile strength, σ_{ys} yielding strength, E Young's module, ν Poisson's ratio.

σ_{uts} and σ_{ys} are taken directly from the `ASTM B-221-05` [3] standard while other parameters came from T-slot producer's data-sheets [2] [4] [5].

B Bibliography and references

In order of first appearance:

[1] MindsHub Association. *Progetto CyberOrto*. URL: https://mindshub.it/progetto-cyberorto/.

[2] *Complete Catalog*. V. 6. Tslots by Bonnell Aluminum. 2021.

[3] ASTM. *ASTM B-221-05 - Standard Specification for Aluminum and Aluminum-Alloy Extruded Bars, Rods, Wire, Profiles, and Tubes*. ASTM B-221-05. ASTM, 2005.

[4] Parker Industrial Profile Systems. *T-Slot Aluminum Framing*. Rev. 5. Parker Hannifin Corporation. 2021.

[5] *Custom Aluminum Framing Systems*. Catalog 23, Part No. L1019. 80/20 Inc. 2019.

A.2 Bill of materials

Table A.2.1: *bill of material and estimated costs.*

Code	Product		Quantity	Price
		Manufacturer		
XXX	General piece		1	€—
XXX	General piece		1	€—
		Manufacturer		
XXX	General piece		1	€—
XXX	General piece		1	€—
			Total:	€100.00

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