A Workspace Analysis of a Overconstrained Cable-Based Parallel Manipulator by Using Interval Analysis

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Abstract

In this paper we present a workspace analysis of a 4-cable driven parallel manipulator by using interval analysis. A prototype has been built and tests have experienced the feasibility of the cable system design and its operation for planar and spatial tasks, even by evaluating the workspace by using the proposed interval analysis procedure.

1. Introduction

Mechanical structure of a cable-based parallel manipulator consists of a moving platform, witch is called end-effector, and a base. These two elements are connected by multiple cables. Indeed, the end-effector is operated by motors that can extend or retract cables. Cable-based parallel manipulators are structurally similar to parallel ones but they have some advantages, if compared to classical parallel manipulators. They have large workspace and few moving parts, which gives good inertial properties. These characteristics make them suitable for applications which require high velocities and accelerations [Melchiorri, 2005]. Other characteristics are high payload-weight ratio, transportability and economical construction. The mechanical system can have a simple structure such that it is easy to manufacture at low cost [Barrette and Gosselin, 2005], [Merlet, 2004] and [Riechel et al., 2004]. It is also possible to obtain re-configurable manipulators relocating connecting points of the cables [Gorman et al., 2001] or actuator position [Merlet, 2006].

Main drawbacks of a cable-based parallel manipulator are due to the cable nature. As first disadvantage must be considered the possible collision of cables with each other, with the load or with the framework is an important problem in spatial redundant systems. Moreover, cables are not rigid so that they can only pull and not push the end-effector, and they must be maintained in tension while the manipulator is operating. It is so important for the working of the manipulator that a definition of "tensionability" can be found in [Landsberger and Shanmugasundram, 1992] as a property for cable-based manipulators which indicates that all of cables must remain in tension under any load if there is a large enough ballast (counteracting) force, which can be generated by spring, gravity, dynamic force or actuator.

Because of cables physical characteristics, workspace analysis and design are different from those that can be referred to parallel manipulators. For obtaining n end-effector-DOFs, it is necessary to use at least $n + 1$ cables, [Ebert-Uphoff, 2004], [Verhoefen, 2004].

This condition ensures to avoid negative tensions in the cable (situation of pushing cable) and increases the payload, but, at the same time, increases the possibility of cables collision and makes the control more difficult [Gorman et al., 2001].

By considering number of cables and degrees of freedom of the end-effector, cable-based parallel manipulators can be classified as "fully constrained" and "under constrained". In the "fully constrained" manipulators the pose of the end-effector can be determined as function of the cables' lengths. In the "under constrained" manipulators the pose of the end-effector is not completely determined by the cables' lengths and the gravity has to be considered as further constrain for solving the problem.

Cable-based parallel manipulators have been used in several kinds of applications.

Because of their high payload-weight ratio, they have been studied for load lifting and positioning [Williams II et al., 2004]. In this field very high loads must be moved and high stiffness and stability are requested to the employed devices.

Cable-based parallel manipulators can have a large workspace and reach high velocities, for these characteristics they can be used in sport recording, as the Skycam^{TM} [Tanaka, 1998] that had been developed as a parallel cable-based system moving a camera in three DOFs of translation.

A further application for this kind of manipulators is, on a smaller size, haptic devices. Also they have been studied as flying simulator and aircraft testing. For moving and orienteering the airplane model during tests, cable-based parallel manipulators can guarantee a good stiffness and large DOFs.

Another field of interest to motion tracking, which is important for virtual reality and biomedical applications. For example, the CATRASYS (Cassino Tracking System) has been used for an experimental identification of kinematic parameters and joint mobility of human arms and legs. The CATRASYS system is a measuring system that has been designed and built at LARM: Laboratory of Robotics and Mechatronics in Cassino. It has been used to determine the position of the limb extremity during its motion and furthermore it is able to measure forces/torques that are exerted by the limb [Ottaviano et al., 2007].

An interesting application field of this class of manipulators is the robot rehabilitation. The use of cable has several advantages. The system is flexible and can be used for various patient postures. Furthermore, cable-based manipulators are light and flexible, human-friendly and safe [Homma et al., 2004]. For example, the MariBot is a 3 d.o.f. wire-based robot characterized by a manually adjustable mechanical structure which is used to support the wires. It has rehabilitation tasks for post-stroke hemiplegic subjects [Rosati et al., 2007].

In this paper a cable-based parallel manipulator is presented. A numerical algorithm has been developed by using interval analysis for the study of its workspace shape and characteristics, even for design and operation purposes to achieve better design and operation.

2. CALOWI (CAssino Low-Cost easy-Operation Wire Robot)

The CALOWI (CAssino Low-Cost easy-Operation Wire Robot) is a 4-cable driven parallel manipulator that has been conceived at LARM: Laboratory of Robotics and Mechatronics in Cassino. It is composed by a mechanical structure, a controller, a PC for programming, suitable end-effector and a tool, as shown in Fig. 1. A suitable design has been done in order to obtain a low-cost and easy-operation manipulator.

The actuation system of the proposed manipulator is composed by four DC motors, which can extend or retract cables. The cable-driven parallel manipulator has a cubic structure in order to operate it for both planar and spatial tasks. In particular, for planar tasks it has been chosen a squared fixed base, as shown in Fig. 2 a), in order to obtain a symmetrical architecture. Since the cable driven parallel manipulator has four cables, it will operate as “fully constrained” manipulator for planar tasks, and as “under constrained” manipulator for spatial tasks.

In Fig.2 b) a laboratory test is shown for simulating a rescue operation in disaster area due to seismic events, [Ottaviano et al., 2005].

In the first version of the prototype two attachment points have been considered at the end-effector. Indeed, the four cables are connected two by two, to the end-effector through two attachment points, as shown in Fig. 2 a). This choice has been made in order to obtain the largest orientation capabilities and closed-form formulation of the kinematics.

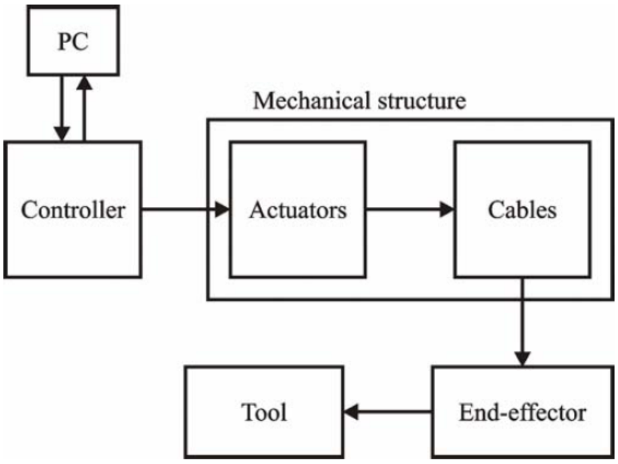
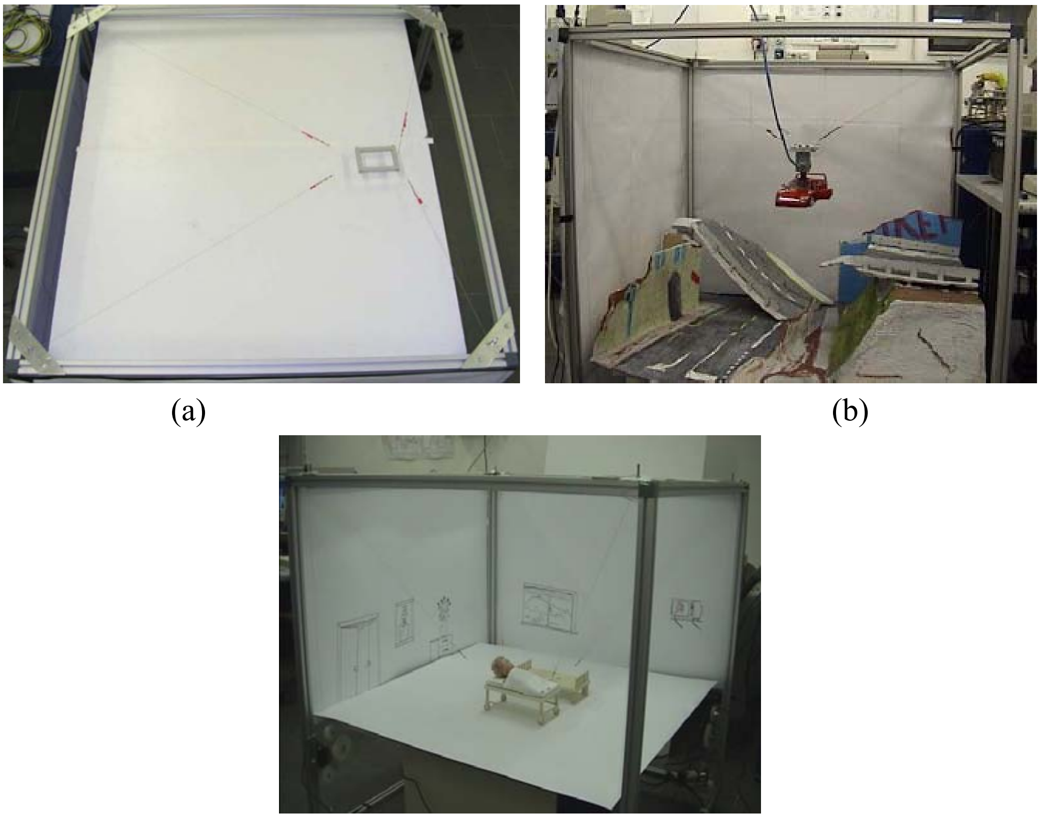


Fig. 1 A scheme for a low-cost easy-operation cable driven parallel manipulator.

The latter version has been designed for operating in hospital for an application in hospital environment, which consists in carrying injured or disabled people with reduced mobility that need to be moved from one location to another in a hospital room (Ottaviano et al., 2007). The end-effector has a rectangular shape with four attachment points, as shown in Fig. 2 c), in order to ensure a given orientation of the platform.

The overconstrained operation feasibility has been tested in accurate path generation. Investigations are undergoing to develop suitable algorithm for intelligent path generator avoiding obstacles [Lahouar et al., 2007]. The problem of cable tension constraint has been approached by designing suitable systems for tension monitoring [Ottaviano et al., 2006].



(a) (b)

(c)

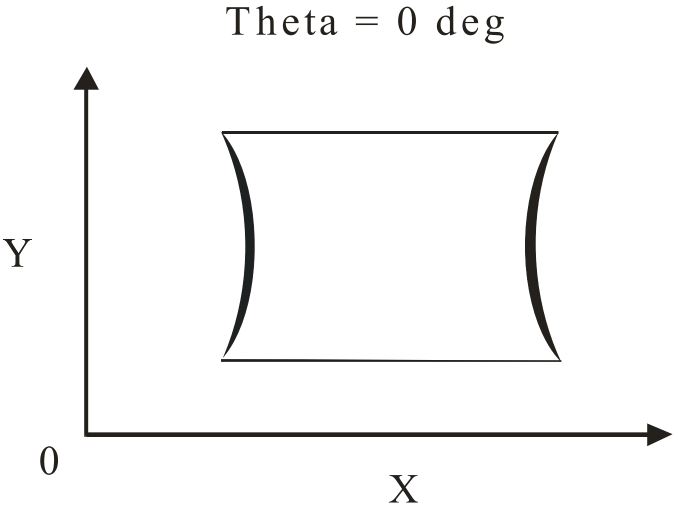
Fig. 2 CALOWI applications: a) path generation by using CALOWI in overconstrained planar configuration: b) rescue operation by using CALOWI in underconstrained spatial configuration; c) simulation of CALOWI operating in hospital environment.

3. Workspace characteristics

One of the most important aspect of cable driven parallel manipulators is the study of the workspace. The workspace is the set of position and orientation in which

- the end-effector is controllable;
- tensions in cables are positive;
- forces value lies between a minimum, because cables must be maintained in tension, and a maximum, in order to avoid the cables break;
- the end-effector is far from singularities;
- cables wrapping is avoided.

Several definition of different workspace can be found in literature.
For example in [Verhoefen, 2004] with the term "controllable workspace" is denoted the set of all postures where the platform can be controlled with positive tensions.
, [Bosscher and Ebert-Uphoff, 2004], [Gouttefarde and Gosselin, 2006], [Gouttefarde et al., 2006].



4. A numerical technique: interval analysis

Interval analysis is a numerical method that can be used successfully for solving a system of equations and inequalities in a given search space.
An "interval" for a variable x can be written as $\mathbf{x} = [\underline{x}, \overline{x}]$ and represents values for *x* such that $\underline{x} \leq x \leq \overline{x}$. The "width" of an interval ***x*** is defined as $\overline{x} - \underline{x}$. If $\overline{x} = \underline{x}$ then **x** is a "point interval".
A "box" for a set of *n* variables $x_1,..., x_n$ is a set $\{\mathbf{x_1,..., x_n}\}$ of intervals for all these variables. The width of a box is the largest width of its interval.
If f is a real-valued function of n variables $\{x_1, ... x_n\}$ an "interval evaluation" F of f is an interval $\mathbf{f}=[\underline{f}, \overline{f}]$ for given ranges $\{X_1, . . . ,X_n\}$ for the unknowns such that

$$\forall X = \{x_1, . . . , x_n\} \in X = \{X_1, . . . ,X_n\} \qquad (4.1)$$
$$\underline{f} \leq f(X) \leq \overline{f} \qquad (4.2)$$

$\overline{f}$ and $\underline{f}$ are upper and lower bounds for the values of f when the unknowns are restricted to lie within the box X.
There are several methods for calculating an interval evaluation of a function as outlined in [Hansen 1992] and [Moore, 1979]. The simplest is the natural evaluation in which all the mathematical operators in f are substituted by their interval equivalent to obtain F. Interval equivalents exist for

all the classical mathematical operators. Interval arithmetic can be used for calculating an interval evaluation for most non-linear expressions.

Interval analysis has several useful properties. OR example, if $F(X) < 0$ or $F(X) > 0$, then there is no value of the unknowns in the box X such that f (**X**) = 0. Furthermore, the bounds of the interval evaluation F usually overestimate the minimum and maximum of the function over the box X, but the bounds of F are exactly the minimum and maximum if there is only one occurrence of each unknown in f.

Algorithms developed by using interval analysis have been used for solving several kinds of problems in robotics.

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5. Determination of the workspace by using interval analysis

The aim of this work is to use interval analysis for the study of the CALOWI properties.

The workspace in the planar case has been studied. The workspace of a cable robot has several constrains and limitations. In this case a first limitation, given by the physical dimensions of the structure, has been considered. The second step for the development of the algorithm has been to consider the nature of the cables that can only pull and not push, and consequently the forces exerted by the cables must only be positive. The workspace obtained can be defined as the set of all poses for which the end-effector can be moved with positive tension in the cables.

A scheme of the 4-cable parallel manipulator is shown in Fig. 3. Two reference frames have been considered. Oxy is the fixed reference frame, which origin O is coincident with point A_1 on the base. O'x'y' is the moving reference frame, which origin O' is coincident with point G on the end-effector.

The boundary of the robot has a square shape with dimension L. The lengths of the four cable are variables and have been indicated with l_i (i=1,..,4). Cables are connected to the base at points A_i (i=1,..,4). The two pairs of cables have coincident attachment point A and B, whose coordinates, with respect to the fixed frame are given by (x_A,y_A) and (x_B,y_B), respectively.

The end-effector has dimension 2h, and the centre of mass G is supposed to be coincident with the origin O' of the moving reference frame.

The pose of the end-effector is given by the coordinates of the point G and θ angle, which is the angle between x and x'.

The Inverse Kinematics Problem (IKP) of the planar 4-cable driven manipulator can be formulated as finding the cable lengths l_i as function of the end-effector pose. This formulation can be used for a numerical study of workspace characteristics of CALOWI, in planar operations.

Coordinates of points A and B, respect to the fixed frame, can be expressed as in Eqs. 5.1

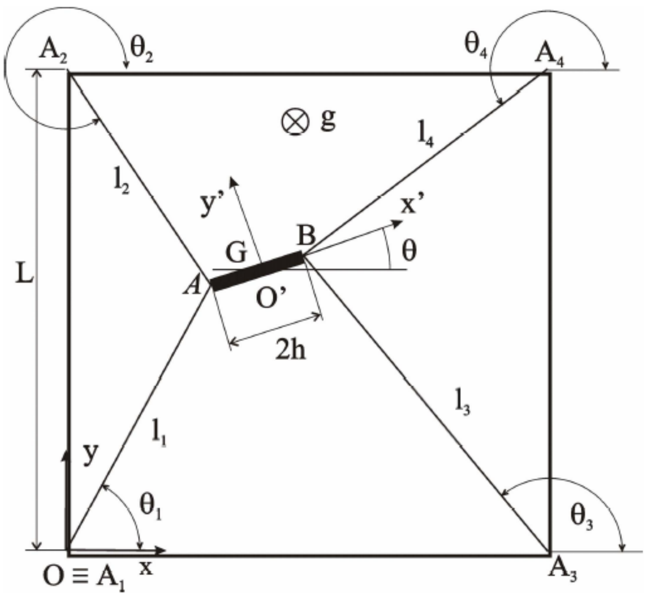


Fig. 3 A scheme for planar operation of CALOWI and its parameters.

$$\begin{aligned} x_A &= x_G - h\cos(\theta); \\ y_A &= y_G - h\sin(\theta); \\ x_B &= x_G + h\cos(\theta); \\ y_B &= y_G + h\sin(\theta). \end{aligned} \qquad (5.1)$$

The IKP of the planar 4-cable driven manipulator can be formulated as

$$\begin{aligned} l_1 &= \sqrt{x_A^2 + y_A^2}; \\ l_2 &= \sqrt{x_A^2 + (L - y_A)^2}; \\ l_3 &= \sqrt{(L - x_B)^2 + y_B^2}; \\ l_4 &= \sqrt{(L - x_B)^2 + (L - y_B)^2}. \end{aligned} \qquad (5.2)$$

As first constrain it is imposed that the position of point G, whose coordinates are x_G and y_G, must be within the limits

$$\begin{aligned} h \le x_G \le L - h; \\ 0 \le y_G \le L \end{aligned} \qquad (5.3)$$

This constrain must to be expressed by using interval analysis

$$\begin{aligned} \overline{x}_G &\le (L - h) \\ \underline{x}_G &\ge h \\ \overline{y}_G &\le L \\ \underline{y}_G &\ge 0 \end{aligned} \qquad (5.4)$$

where $\overline{x}_G$ and $\overline{y}_G$ are the upper endpoints of the interval given by the coordinates of point G, and $\underline{x}_G$ and $\underline{y}_G$ are the lower endpoints of the same interval.

It is necessary to consider the important limitation due to the unidirectional nature of the forces exerted by the cables, and it is necessary to add such a constrain in order to obtain the desired workspace. Considering this peculiar characteristic many studies have been made mainly in the planar case [Barrette and Gosselin, 2005], [Oh and Agrawal, 2005], [Gouttefarde and Gosselin, 2006], [Stump and Kumar, 2004].

There is a mathematical connection between the cable robots and grasping. Forces exerted from fingers to the grasped object are also unidirectional because the fingers can only push and not pull [Ebert-Uphoff and Voglewede, 2004]. In [Voglewede and Ebert-Uphoff , 2005] the definition of a "force closure pose" is given as a particular pose of a cable robot for which any arbitrary external wrench applied to the end-effector can be counteracted through appropriate tension forces in the cables.

As can be seen, for example, in [Fattah and Agrawal, 2002] a planar cable robot must use minimum four cables for obtaining a force closure, but this is not a sufficient condition. The "planar antipodal cable theorem" [Voglewede and Ebert-Uphoff, 2005] proves that a planar cable robot with two pairs of cable with coincident attachment points A and B is force closed if, and only if, the line from A to B lies fully in the two open force triangles defined by the reverse forces of the two cable pairs. Considering, for example, the configuration in Fig. 4 (θ positive) the planar antipodal cable theorem is satisfied if

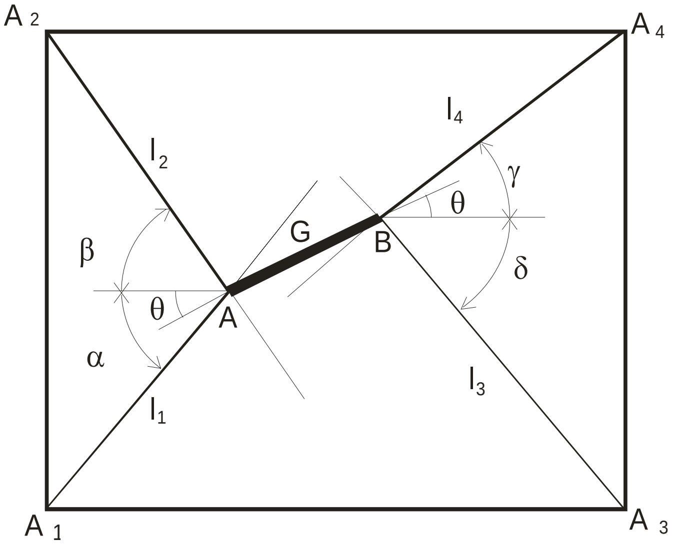


Fig. 4 A scheme for the determination of CALOWI's constrains.

$$\begin{aligned} C1 &\leq C2 \\ C3 &\leq C4 \end{aligned} \qquad (5.5)$$

By using interval analysis

$$\begin{aligned} \overline{C1} &\leq \underline{C2} \\ \overline{C3} &\leq \underline{C4} \end{aligned} \qquad (5.6)$$

whereC1, C2, C3, C4 are given by

$$\begin{aligned} &C1=(y_B-y_A)x_A \\ &C2=(x_B-x_A)y_A \\ &C3=(y_B-y_A)(L-x_B) \end{aligned} \qquad (5.7)$$

$$C4=(x_B-x_A)(L-y_B)$$

If θ is negative, the planar antipodal cable theorem is satisfied if

$$\begin{aligned} C1 &\le C5 \\ C3 &\le C6 \end{aligned} \qquad (5.8)$$

By using interval analysis

$$\begin{aligned} \overline{C1} &\le \underline{C5} \\ \overline{C3} &\le \underline{C6} \end{aligned} \qquad (5.9)$$

whereC5, C6 are given by

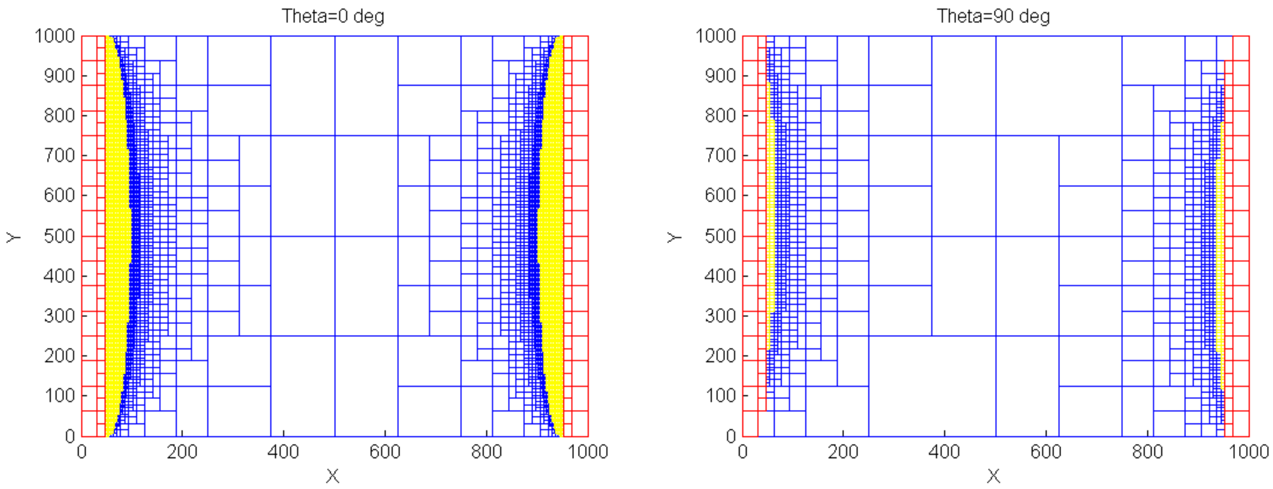
$$\begin{aligned} &C5=(x_B-x_A)(L-y_A) \qquad (5.10) \\ &C6=(x_B-x_A)y_B \end{aligned}$$

6. Numerical results of the workspace analysis

An algorithm has been developed in order to obtain the workspace evaluation. It uses a bisection procedure starting from an initial box in which the variables x_G, y_G and θ have the range with the largest width.
The algorithm does the following steps

1. given a box, tests if the constrains are satisfied,
2. if all the constrains are satisfied then the box is fully inside the workspace,
3. else if all the constrains are not satisfied, then the box is fully outside of the workspace,
4. else if conditions at points 1 and 2 are not true, the box is bisected (until its dimension is larger then a fixed ε) and then go to 1.

Figures 5 a) and b) show all possible locations of point G on the end-effector which can be reached with a fixed orientation. In Fig. 5 a) the orientation is given by θ = 0 deg, and in Fig. 5 b) the orientation is given by θ = 90 deg. Blue boxes represent the possible locations of the point G which are fully inside the workspace. Red boxes represent the locations of point G which are outside the workspace. Yellow boxes represent the locations for which it was impossible to establish if G is in or out of the workspace for the given accuracy (ε).
Table 1 gives an account of the computation algorithm in terms of computation time (t), accuracy (ε), number of boxes, range of parameters (x_G, y_G, θ).



(a) (b)

Fig. 5 CALOWI’s workspace obtained for a constant orientation of the end-effector given by: a) θ = 0 deg; b) θ = 90 deg.

ε	**t** (s)	**[x_G]** (mm)	**[y_G]** (mm)	**[θ]** (deg)	**Boxes in** (blue)	**Boxes out** (red)	**Boxes doubt** (yellow)
7	0	[0, 1000]	[0, 1000]	[0, 0]	3152	96	5220
3	0	[0, 1000]	[0, 1000]	[0, 0]	8752	608	14000
8	0	[0, 1000]	[0, 1000]	[90, 90]	1072	92	292
7	0	[0, 1000]	[0, 1000]	[90, 90]	2186	92	0
15	1	[0, 1000]	[0, 1000]	[0, 90]	6796	316	14990
10	1	[0, 1000]	[0, 1000]	[0, 90]	11410	316	25366

Table 1 Results of computation obtained by applying the algorithm in which constrains expressed in Eqs. 5.4 are considered.

Figure. 6 a) shows cross sections of all possible locations of point G on the end-effector, which can be reached with fixed orientations obtained for θ = 0-15-30-45-60-80-90 deg.

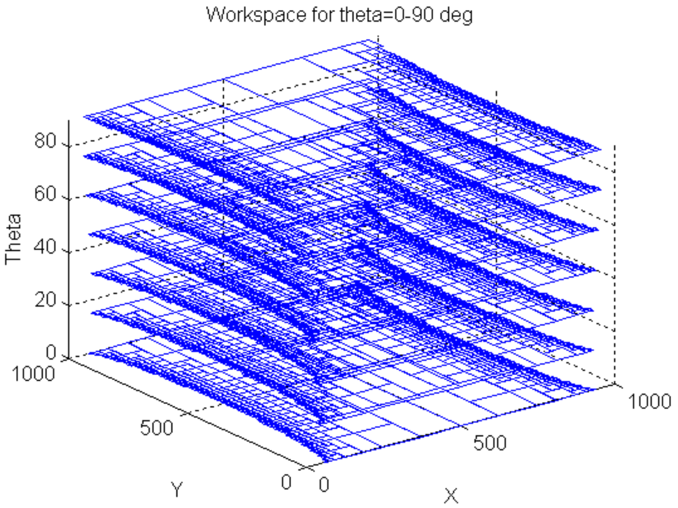


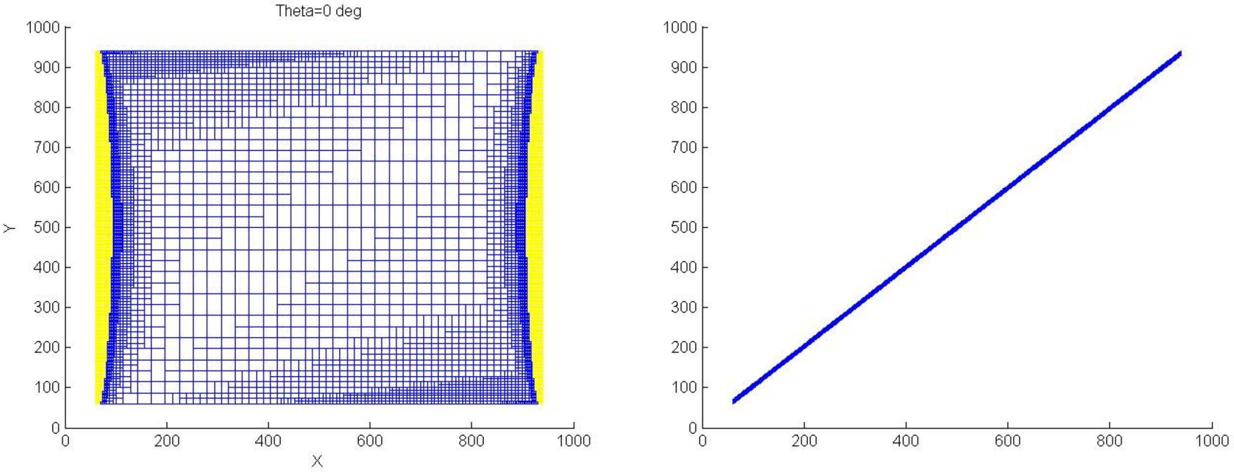
Fig. 6 CALOWI’s workspace obtained for the orientation of the end-effector given by: θ = 0-15-30-45-60-80-90 deg.

A more realistic result has been obtained by adding to the algorithm constrains formulated in Eqs. 1.6 and relative to the nature of the cables.

Figures 7 a) and b) show all possible locations of point G on the end-effector, which can be reached with a fixed orientation. In Fig. 7 a) the orientation is given by $\theta = 0$ deg, and in Fig. 7 b) the orientation is given by $\theta = 44$ deg.

Figure 8 shows cross sections of all possible locations of point G on the end-effector, which can be reached with fixed orientations obtained for θ = 0-15-30-45-60-80-90 deg.

Table 2 gives an account of the computation algorithm in terms of computation time (t), accuracy (ε), number of boxes, range of parameters (x_G, y_G, θ).



(a) (b)

Fig. 7 CALOWI's workspace obtained for a constant orientation of the end-effector given by:
a) $\theta = 0$ deg; b) $\theta = 44$ deg (only boxes in the workspace).

ε	**t** (s)	**[x_G]** (mm)	**[y_G]** (mm)	**[θ]** (deg)	**Boxes in** (blue)	**Boxes out**	**Boxes doubt** (yellow)
10	0	[60, 940]	[60, 940]	[0, 0]	3018	0	1622
5	0	[60, 940]	[60, 940]	[0, 0]	5346	0	4020
1	2	[60, 940]	[60, 940]	[44, 44]	12568	38612	55950
10	0	[60, 940]	[60, 940]	[0, 45]	15574	10878	50534
5	0	[60, 940]	[60, 940]	[0, 45]	84260	57696	222626

Table 2 Results of computation obtained by applying the algorithm in which constrains expressed in Eqs. 5.6 are considered.

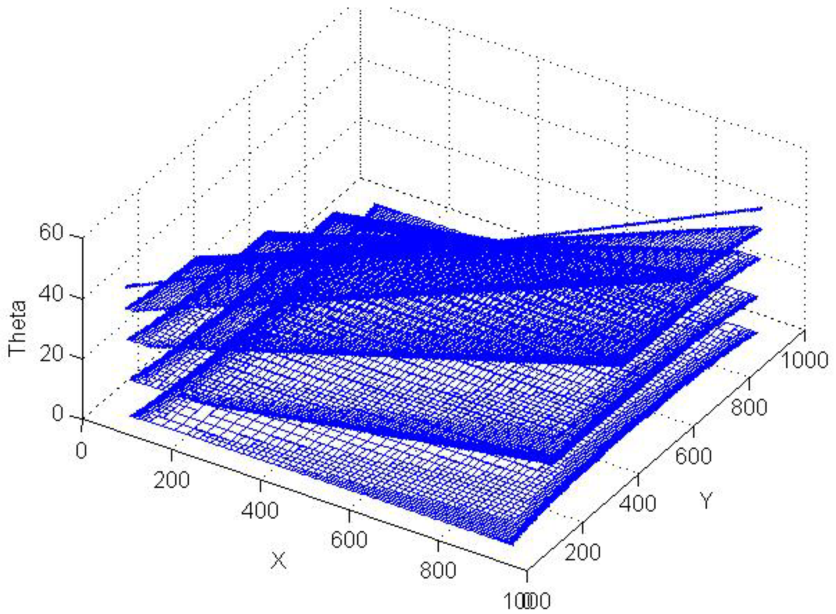


Fig. 8 CALOWI's workspace obtained for the orientation of the end-effector given by:
a) θ = 0-12-25-35-44 deg.

Moreover results have been obtained by considering constrains formulated in Eqs. 1.9.

Figures 9 a) and b) show all possible locations of point G on the end-effector which can be reached with a fixed orientation. In Fig. 9 a) the orientation is given by θ = 0 deg, and in Fig. 7 b) the orientation is given by θ = -44 deg.

Figure 10 shows cross sections of all possible locations of point G on the end-effector which can be reached with fixed orientations obtained for θ = 0 – (-10) – (-20) – (-30) – (-44.9) deg.

Table 3 gives an account of the computation algorithm in terms of computation time (t), accuracy (ε), number of boxes, range of parameters (x_G, y_G, θ).

ε	**t** (s)	**[x_G]** (mm)	**[y_G]** (mm)	**[θ]** (deg)	**Boxes in** (blue)	**Boxes out** (red)	**Boxes doubt** (yellow)
10	0	[60, 940]	[60, 940]	[-44, -44]	226	392	504
1	0	[60, 940]	[60, 940]	[-44.9, -44.9]	1554	3272	4089
2	3	[60, 940]	[60, 940]	[-10, 0]	55306	1446	100578

Table 3 Results of computation obtained by applying the algorithm in which constrains expressed in Eqs. 5.9 are considered.

(a) (b)

Fig. 9 CALOWI's workspace obtained for a constant orientation of the end-effector given by:
a) θ = 0 deg; b) θ = - 44 deg.

Fig. 10 CALOWI's workspace obtained for the orientation of the end-effector given by
θ = 0 – (-10) – (-20) – (-30) – (-44.9) deg.

7. Conclusions

In this paper the CALOWI prototype has been presented. The CALOWI's workspace has been studied in the planar case by developing an algorithm based on interval analysis and bisection process. The obtained results are related to the locations of point G on the end-effector which can be reached with fixed orientations. Findings are also be found for all possible locations of point G on the end-effector which can be reached with orientation included in a given set.
This work can be seen as a first step toward the determination of the CALOWI workspace also in the three-dimensional case. Moreover can be of interest to apply some filtering technique in order to improve the obtained results.

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