2010 IEEE International Conference on Robotics and Automation
Anchorage Convention District
May 3-8, 2010, Anchorage, Alaska, USA

A portable, modular parallel wire crane for rescue operations

J-P. Merlet and D. Daney

Abstract— **This paper presents the preliminary development of a full scale, portable, modular, fully autonomous parallel wire crane that is intended to be used for rescue operations. This design is innovative in terms of flexibility for managing the location of the anchor points of the cables on the ground and on the platform, the possibility of partial platform location control through the management of the kinematics with less than 6 cables and the availability of on-board sensors allowing to possibly locate victims through thermal imaging and to transmit physiological data on the victims while they are still moving toward a safe area.**

I. INTRODUCTION

A. NEEDS

Availability of heavy lifting crane is major issue for rescuing people after a natural catastrophe. To illustrate this need we may quote the Independent newspaper after the 8/18/1999 earthquake in Turkey: *Throughout Golcuk, people were frantic to save loved ones and friends. Some refused to lose hope, digging with their hands, hour after hour …Mahir Eryilmaz dug for 12 straight hours, trying to free his nephew. When a crane finally arrived, its reach wasn't long enough.* or Skynews after the 5/15/2008 earthquake in China: *Rescuers efforts have been hampered by landslides, buckled roads, collapsed bridges and wet weather. The Chinese government has made an emergency appeal for cranes and heavy lifting equipment amid warnings that time is running out for survivors of Monday's 7.9-magnitude quake.* We may also quote [1]: *Means of Lifting (Priority: High) A means of lifting heavy items that is stable, quick to set up, and can be placed close to the work site is needed. Currently, cranes are often used at disaster sites, but they are not part of the US&R equipment cache. They are typically obtained from local sources. As a result, a crane, if it is even available, may take a long period of time to locate and obtain. Other lifting equipment currently used includes winches, "comealongs", and pulleys that are often attached to either tripods or "A-frame" assemblies. These systems can be set up rather quickly but may have some limitations in regard to lifting capacity and stability on uneven surfaces.*

B. PARALLEL WIRE-DRIVEN CRANE

In a parallel wire-driven crane the robot's platform is connected to the ground through a set of cables (usually 6) that can be coiled and uncoiled on a drum that is actuated by a rotary motor. Appropriate control of the cable lengths allows one to fully control the platform pose. Parallel wire-driven robots have already been proposed for cranes [2], [3], [4], [5], [6], [7], especially as a rescue engine [8]. But to the best of our knowledge a full scale, truly portable rescue crane has never been build. Furthermore rescue operations require specific functionalities such as localization of victims, ease of deployment and control, large workspace and ability to be used with less than 6 cables. We will address all of these issues.

II. HARDWARE

A. WINCH

Our winch (figure 1) is constituted of a low cost classical car winch EW 2300 that has been modified to incorporate a 200W motor/encoder and adaptable driving belts. This winch provides a tension from 1700 N up to 10000 N with a coiling speed from 0.17 m/mn up to 14 m/mn. Several type of cables may be used with this winch, allowing to use a cable length from 15m to up to almost 90m. As cable we are using 3 to 5 mm steel wires and/or 2 to 4 mm Kevlar wires.

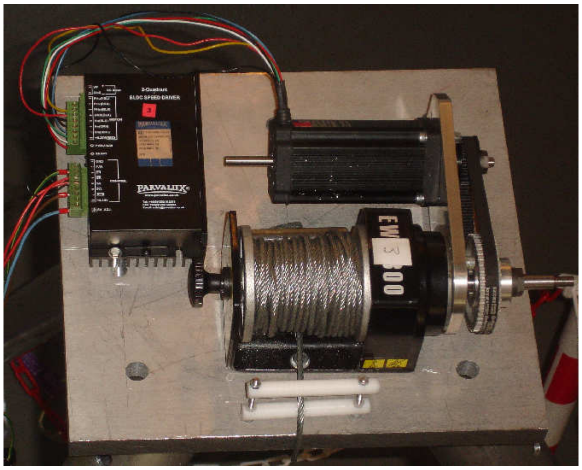

Fig. 1. One crane winch

This winch is put on a rotating head that can be attached to tripods or other supporting element. Its weight is about 15 kg but may be reduced to less than 10 kg. A major problem with this type of winch is to determine the cable length ρ that we must measure for control purposes. The change of cable length according to the motor rotation depends upon the number of layers on the drum. Although measuring the motor rotation allows one to get ρ with an accuracy of a few centimeter we intend to improve this accuracy by gluing a magnetic tape at some calibrated point on the cable and to use a Hall effect sensor to calibrate the cable length.

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978-1-4244-5040-4/10/$26.00 ©2010 IEEE

Being given the winches characteristics we may safely assume that the crane may manipulate at least a 1 ton load and probably more at least in some part of its workspace. Accuracy has yet to be determined experimentally but we have already determined ways to improve it: measuring more accurately the cable lengths, taking into account the elasticity [9] and sagging [10] of the cables in the kinematics and obtaining direct measurements on the location of the platform.

B. *SUPPORTING ELEMENTS AND PLATFORM ATTACHMENTS*

The rotating head has been designed so that it can be attached to any high elements on site. Portable tripods with a maximum height of 3m, that can be strongly attached on the ground, may also be used. This is illustrated in figure (2) where the system is shown in its 4-2-2 configuration (four cables attached by pairs at two points on the platform).

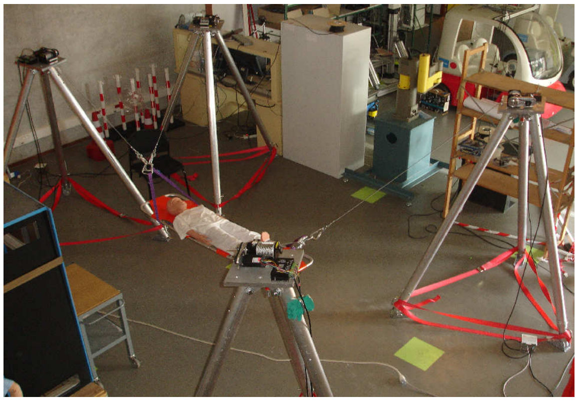

Fig. 2. The crane in a 4-2-2 configuration (4 cables attached to 2 pairs of points on the platform)

As for the attachment points of the cables on the moving rigid body we may use calibrated platforms (such as the stretcher shown on figure (2) that may be connected to the cable with snap links. We may also have to attach the cable to elements that are not known in advance (such as walls, beams, . . .). In that case we plan to use suction pads, belts and hoisting eyes.

Currently the weight of the fully autonomous system is 451 kg: 90 kg for the rotating heads, 264 kg for the tripods, 30 kg for the power wires, 15 kg for the computer, communication boards and sensors, 30 kg of belts, suction pads and 22 kg for the power generator. Although this is a large number (that may be probably be reduced to about 300 kg), it is still within the capability of a rescuers team, especially as the crane may be decomposed in elements whose weight is 15 kg or less.

C. *COMMUNICATION AND SENSORS*

For large systems it may be difficult to connect each winch system with power and communication wires. For power requirement portable generators will be used if necessary. For communication purpose we will establish a wifi lan enabling to connect the winches to the master computer, using SOFIM axoLAN modules.

The platform may have also to be connected. For example it may be necessary to locate victims in a relatively large area (typically a square area with an edge of 100 meters). For that purpose the robot platform may be a balloon whose motion will be controlled by the robot and we have experimented the use of a thermal camera to locate victims. It appears that victim are clearly visible on the image, even from a large distance (over 50m), figure (3), and seems to be superior than using GSM as proposed in [11], [12]. The obtained image should be transferred from the platform to the computer with a low weight system (as the load supported by the balloon is relatively low): for that purpose we plan to use a Sun SPOT device, which weights on 74 grams and has on board wifi, a 3-axis accelerometer (that may help to locate and control the platform) and other possible sensors inputs. As soon as victims are located the robot will be configured as a crane (we may possibly have two drums on the winch: one of large diameter for the light wire connected to the balloon and one for the crane cables).

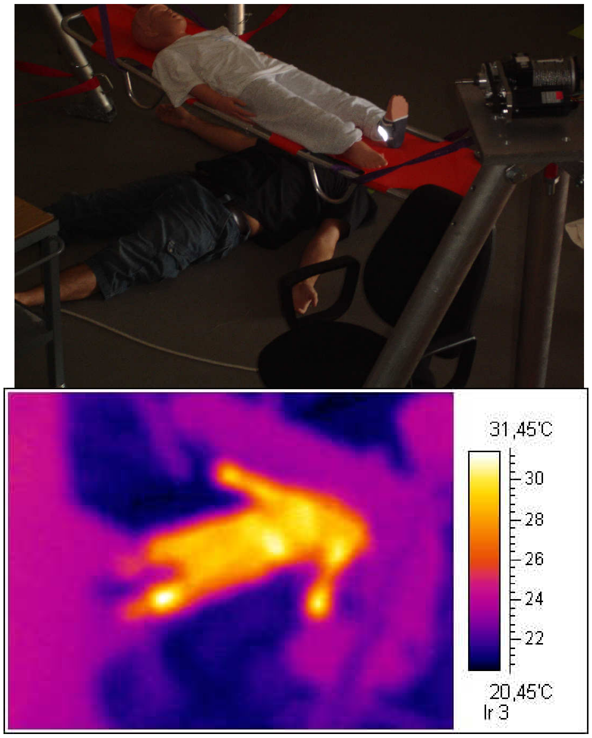

Fig. 3. An image of the thermal camera showing clearly a victim from a distance of 50 meters

Another use of the Sun SPOT during a rescue operation will be to provide physiological measurements on the victim while he/she is still being moved by the crane (for example the SPOT has already an in-board temperature sensor that may be used to monitor the victim and we plan to use also a cardiometer). The on-site rescuer will plug a physiological kit on the victim and the measured signals will be transmitted to a base station so that doctors may prepare their intervention.

Interface to the robot will be a simple 6D joystick or even a push-buttons device that will be connected to the lan. Control and management of the sensors is performed through a classical workstation running a real-time Linux.

III. KINEMATICS AND CONTROL

A. *INVERSE AND FORWARD KINEMATICS*

It is first necessary to define a nomenclature for this type of system. We will denote by $n - m_1 - \dots m_n$ a robot having n cables, m_i being attached at one point on the platform (hence the sum of the m_i should be equal to n). If all the m_i are equal to 1, then we will use the $n - n$ shortcut. Hence a 6-6 robot has 6 cables, each of which is attached at a distinct point on the platform, while a 4-3-1 will have 4 cables, three of them attached at the same point, the last cable being attached at another point.

Basic equations governing the kinematics are the relations between the cable lengths ρ and the pose parameters $\mathbf{X}$ but as we are using the robot as a crane we have also to consider the static equations relating the tension τ in the cables to the wrench $\mathcal{F}$ applied on the platform.

Let us define a reference frame $O, \mathbf{x}, \mathbf{y}, \mathbf{z}$ and a frame $C, \mathbf{x_r}, \mathbf{y_r}, \mathbf{z_r}$ attached to the platform. Let A_i be the attachment point of the cable on the ground and B_i their attachment point on the platform. We have

$$\mathbf{A_iB_i} = \mathbf{A_iO} + \mathbf{OC} + \mathbf{RCB_i^r} \qquad (1)$$

where $\mathbf{R}$ is the rotation matrix between the reference frame and the mobile frame, $\mathbf{CB_i^r}$ the coordinates of B_i in the mobile frame and $\mathbf{OA_i}, \mathbf{CB_i^r}$ are the coordinates of the attachment points on the base and on the platform, that are supposed to be known (see the ”Calibration” section).

The pose parameters define $\mathbf{OC}, \mathbf{R}$ and we have

$$\rho_i^2 = ||\mathbf{A_iB_i}||^2 \qquad (2)$$

As for the statics it is well know that if we define a Jacobian matrix $\mathbf{J}$ with as i-th row J_i

$$J_i = ((\mathbf{A_iB_i}/||\mathbf{A_iB_i}||, \mathbf{CB_i} \times \mathbf{A_iB_i}/||\mathbf{A_iB_i}||))$$

then at a mechanical equilibrium state we have

$$\mathcal{F} = J^{-T}(\mathbf{X})\tau \qquad (3)$$

1) *INVERSE KINEMATICS:*

Inverse kinematics (IK) consists in finding the ρ for reaching a given pose $\mathbf{X}$ when the platform is submitted to a given wrench. For a n wires robot equations (2) is a system of n equations in the ρ unknowns while (3) is a system of 6 equations with as unknowns the n τ, which must all be positive to ensure that the cables are under tension. Overall we have a system of $6+n$ equations with $2n$ unknowns, which is square for $n = 6$ and over-constrained for $n < 6$. Hence to obtain a finite set of solution in the ρ (i.e. dealing with a square system of equations) we may only fix n d.o.f for the platform pose parameters (and consequently the system has n d.o.f.) while $6 - n$ pose parameters cannot be fixed. Such system has been extensively studied for $n \geq 6$ [13] but it is necessary to study this problem also for $n < 6$. Indeed during a rescue operation we may have to disconnect one or several cable (e.g. to avoid obstacles) or we may not be able to implement a six cables robot due to the topography of the terrain. The literature on the IK for $n < 6$ is sparse[14], [15], [16], [17] and we are currently investigating all cases with 1 to 5 active cables. This problem is quite difficult: for example it may be shown that the IK of a 2 wires robots already involves solving a 4th order polynomial. A wire-driven robot in a crane configuration with n cables allows the control of n d.o.f. If $n < 6$, then we will have to decide which d.o.f. are important and we aim at providing a method allowing to determine all possible cable lengths for a given set of n generalized coordinates. However we may need some flexibility: for example for a rescue operation it will be necessary to control the location of the center of gravity of the platform but at the same time the normal to the platform should remain relatively close to the vertical. Hence this problem may be formulated as follows: being given a desired location of the center of gravity $\mathbf{X_d}$ and a maximal angle between the normal of the platform and the vertical determine the closest pose to $\mathbf{X_d}$, which satisfies the angular constraint and also (3) with positive tension in the cables. Note that the solution may be a configuration in which $m < n$ cables are used, the tension in the $n - m$ other cables being 0. Clearly such a constrained optimization problem is difficult to solve.

2) *FORWARD KINEMATICS:*

Forward kinematics (FK) consists in finding the pose $\mathbf{X}$ being given the cable lengths when the platform is submitted to a given wrench. For a n wires robot equations (2) is a system of n equations in the 6 unknown pose parameters while (3) is a system of 6 equations with as unknowns the n τ, which must all be positive to ensure that the cables are under tension. Overall we have a square system of $6 + n$ equations with $6 + n$ unknowns. Note that the system is decoupled: the 6 equations (3) are linear in the n tau, n may be solved, leaving $6 - n$ equations in the components of $\mathbf{X}$. Combined with the n equations of (2) we end up with 6 equations in the 6 components of $\mathbf{X}$, that is much more complicated than the classical FK problem for parallel robots with rigid legs. We have developed a solving scheme using interval analysis that allows one to compute all solutions but the computation time is high (more than one hour may be needed) but a real-time algorithm has also been developed based on a certified Newton scheme [18].

3) *TRAJECTORY CONTROL:*

For trajectory control we use velocity control: if $\mathbf{T}, \Omega$ denotes the translational and angular velocities of the platform and $\dot{\rho}$ the wires velocities, then we have

$$\dot{\rho} = \mathbf{J^{-1}}(\mathbf{X})(\mathbf{T}, \Omega)$$

This relation is used to calculate the wire velocities to perform a desired motion with given velocities. But this relation implies to determine the current platform position during the motion, being given the cable lengths i.e. to solve the forward kinematics problem (FK). Note that however we may have to start the robot is a given pose so that we can initialize the real-time FK.

It must also be mentioned that even for a robot having $n \geq 6$ cables it may be necessary to be able to solve both the IK and FK for less than 6 wires. Indeed during the robot motion it may occur that we cannot ensure a positive tension in one or several cables: this should not impede the possibility of controlling some d.o.f. of the platform.

B. OTHER KINEMATICS PROBLEMS

The IK and FK are not only the only kinematics problems that we may have to solve for this application.

It may happen for example that we have a priori information on the search space that will have to be covered, including zones in which we may install the winches and/or the tripods. This is a topic we have investigated since a long time and we are able to determine 3D zones for the ground attachment point of each winch so that a given workspace will be covered and the positioning accuracy at each pose of this workspace will be better than a given threshold [19], [20]. Obtaining these zones allows to manage the uncertainties that are unavoidable when implementing a theoretical solution: provided that the location of the anchor points still lie within the zones, then we will still be able to reach the desired workspace.

Another kinematic problem is related with possible interference between the cables, that may restrict the workspace. We have already addressed this problem [21] and we have developed an efficient algorithm that allows one to check a trajectory for possible collision or compute the interference-free workspace.

Another important problem is induced by the possible necessity of having to disconnect one wire during one robot motion (e.g. if the cable comes close to an obstacle). In that case we start with the robot in a given pose $\mathbf{X_1}$ with n wire having a positive tension and we want to move to another pose $\mathbf{X_2}$ as close as possible from $\mathbf{X_1}$ for which the tension in one of the wire becomes 0, so that a rescuer can disconnect it. Then the robot will be moved using only $n-1$ wires until the free wire may be reconnected. Note that we may have constraints on the motion between $\mathbf{X_1}$ and $\mathbf{X_2}$: for example if a victim lie on the platform it will be necessary to limit the tilting angle.

To solve this problem we have to define a closeness index between two poses. Let consider the location of the attachment point B_i of the platform and define B_i^1 their location at pose $\mathbf{X_1}$ and B_i^2 at pose $\mathbf{X_2}$. We define a closeness index $\mathcal{C}$ as

$$\mathcal{C} = \sum_{j=1}^{j=n} ||B_j^1 B_j^2||^2$$

and our objective is to find a $\mathbf{X_2}$ that minimizes $\mathcal{C}$. Furthermore we may impose the additional constraint that the angle between the normal $\mathbf{n_1}$ to the platform at pose $\mathbf{X_1}$ and this normal $\mathbf{n_2}$ at pose $\mathbf{X_2}$ does not exceed a given threshold.

Solving analytically this constrained optimization problem is clearly a very difficult problem but we have designed a numerical algorithm, based on interval analysis, that allows one to calculate a very good approximation of the global minimum, whatever is n, in a reasonable time (usually less than 5 minutes).

IV. CALIBRATION

This modular crane should be able to be quickly mounted and usable. A simple and fast calibration method is a key point for such system [22]. Indeed the location of the winches A_i will not be known in advance and is required for the control. The location of an attachment point A_i is considered as punctual because a constraint system limits the clearance of the cable on the winch output. With regards to our prototype, the error of location is about 0.16% of the variation of cables length (between 0 to 12 m): this error may be neglected.

During the deployment of the crane, it is necessary to define physically the reference frame $O, \mathbf{x}, \mathbf{y}, \mathbf{z}$. Three calibrated punctual targets denoted O, O', O'' are put on the ground. The center of the reference frame is defined by the first point O, the axis $\mathbf{x}$ along the vector OO' and $\mathbf{z}$ perpendicular to the plan containing O, O' and O''. Distances between each A_i and these targets are measured, allowing the calculation of the location of the winches A_i by trilateration. We use a method based on Cayley-Menger determinants presented in [23], [24] ; note that the location of O, O' and O'' is chosen to improve observability of A_i determination.

The choice of the distance measurement tool has to be adapted to the task. To determine the distance, according to the simplicity and the robustness of the presented crane and its calibration, a tape-measure is sufficient for an accuracy about one centimeter error order. In our experimentation, we prefer a more accurate laser telemeter which is more practical.

The relative positions of the attachment points on the platform B_i have also to be identified. We may use a calibrated platform for which the coordinates of the B_i will be known in advance. But in some cases we will have to adapt the location of these points according to the task. Here again we plan to use the trilateration method.

Finally we need to establish the function relating the cable length to the number of turns as measured by the sensors of each winch's motor. To avoid the problem of the identification of the layer of the cable coiled on the drum, a second order polynomial is used as an approximation of this function. According to our experiment the maximal error between the measurement of the cable length and the polynomial approximation is equal to 0.2% (for a cable length variation between 0 to 12 m).

V. PRELIMINARY EXPERIMENTS

We have performed a preliminary lifting experiments using 4 winches. They were located in the corner of a 12m × 4m rectangle at a height of 2.8m. The cables were attached to a 25kg platform with suction pads and a 75kg mannequin was put on the platform (figure 4). Although the disposition of the winch was not very appropriate (it can be seen on the picture that the angle between the cables and the horizontal is less than 30 degrees), the experiment was a full success. We use then two mannequins without any problem (figure 5). The location of the anchor points on the platform is arbitrary (although the choice may have an influence on the nature of the d.o.f. of the platform). For example figure 6 shows how the cables can be directly attached to a stretcher.

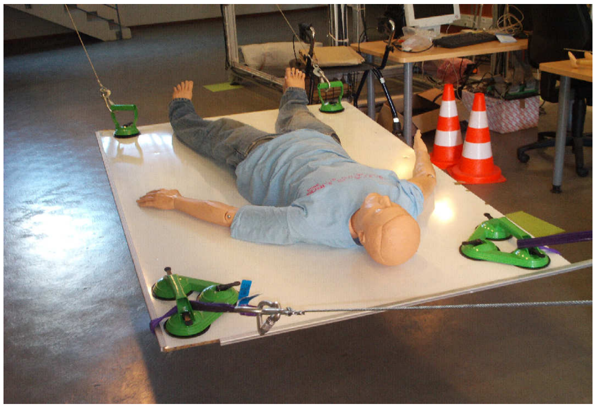

Fig. 4. Lifting of a 75kg mannequin on a 25 kg platform. Note the suction pads that are used to attach the cable on the platform

Fig. 5. Lifting of a 75kg mannequin and a 35 kg mannequin on a 25 kg platform.

Specific medical devices may also be used: for example we have used a stand-assist sling that allow for raising patient (figure 7). This crane may be an interesting alternate for classical ceiling hoist as it offers more d.o.f. and is less intrusive. Furthermore a reduced version of the crane may be used for lifting patients whatever its location on a given room, but also as a manipulation tool that can grasp an object and bring it to the end-user.

We plan to have a full scale experiment involving 6 winches located in a 30m × 20m area and at a height of 12m in October 2009. Results of this experiment will be presented during ICRA.

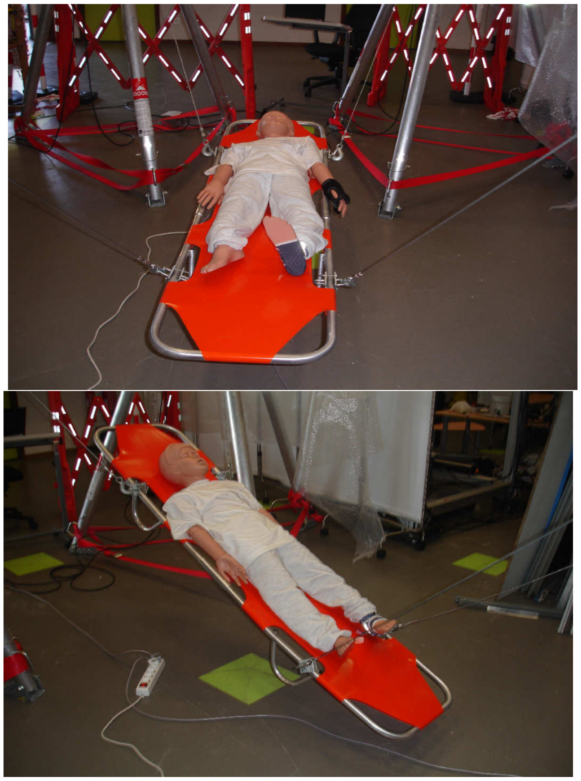

Fig. 6. Connecting the robot to a stretcher.

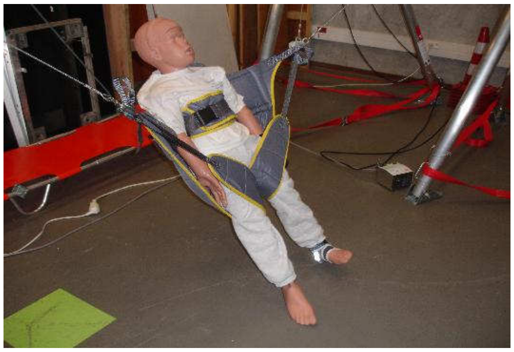

Fig. 7. Moving up with a stand assist belt

Settling time is important for such system when used in rescue operations. Assuming that we have a 3 people team to manage each winch system we estimate that a workable crane will be available within 25 minutes after the hardware arrived on site (including calibrating the system) while a configuration change (i.e. modifying the location of the winches) may be realized in 15 minutes.

VI. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

We have described a full scale modular and portable rescue crane. It allows for a rapid deployment on site and it can also be used as a victim localization device. Preliminary experiments have shown that even in a reduced configuration (4 winches) it was an effective tool to lift at least 100 kg load, while its real capacity will be much larger. Key issues in this development are a full kinematics analysis involving from 2 to 6 cables, accuracy improvements and calibration. This device may play an important role in rescue operations by providing quickly a heavy lift ability in environment where deployment time is of essence and for which more classical solutions may arrive too late.

B. Future Works

Application of wire-driven parallel robot are not restricted to rescue operations. We plan to build a modular crane for helping lifting elderly at home or patient at hospital. Such system will be based on standardized low-cost hardware, will have a very low intrusivity (when not in use it will be hidden in the ceiling), and we will use our design software to determine the best location of the winches within a given room (e.g. the toilets). We are currently building a simulated 15 m^2 flat including a kitchen area, a bedroom and a meal area for testing the use of wire-driven crane as a lifting and manipulation tool. We are also investigating the use of such robot in rehabilitation [25], [26], [27], [28] and sport training tasks [29]. For that purpose we will use another of our prototype that will be close to the simulated flat in combination with rehabilitation and training devices. We are also currently building another large scale prototype using linear actuators to be used in a virtual reality Cave or in entertainment theaters [30], [31].

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