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TM-l5-94
Articulating Robot Arm
Turret/Arm Development

By: Engineering Services Inc.,
Toronto, Ontario

TECHNICAL MEMORANDUM

Submitted by
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Canadian Bomb Data Centre

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NOTE: Further information about this report can be obtained by calling the CPRC information number (613) 998-6343

EXECUTIVE SUMMARY

The Engineering Services Inc.(ESI) in collaboration with the Robotics and Automation Laboratory(RAL), Department of Mechancial Engineering, University of Toronto in consultation with the the R.C.M.P.'s Explosives Disposal and Technology Branch completed a system analysis and conceptual design of the robot. This includes drawings of the robot chassis and drive system as well as the parameters obtained from manufacturers of various system components. Specifically, the study involves the electronics and communication subsystem, disposition of control electronics modules across the system, drive system parameters, batteries, and mechanical parameters of the chassis and wheels. The goal of the study was to determine how the arm under development will influence the overall stability of the system. Static and dynamic simulations of the overall system have been performed by the use of DADS program package. The results of simulation are used to predict the behaviour of the system in a variety of robot arm configurations. It has been shown that the minimum-weight design of the arm is needed to achieve maximum stability of the system.

The second task involved the conceptual design of the robotic arm, disposition and types of actuators, finite-element stress analyses of links to minimize the mass and inertias, selection of materials, conceptual design of the wrist and the winding and pay-out system integration with existing chassis and turret. The conceptual design is based on the following CAD packages: AutoCAD(including 3D solid modeler), and AutoDESIGN. The analytical work has been done in Matlab environment. The conceptual design is also based on the results obtained within the above noted task, that is, the System analyses phase. The CAD and mathematical computer packages provided flexible environment to the design allowing for multiple iteration interactive design. The main results can be summarized as follows:

i) the turret and wrist joints will be driven by DC motors and harmonic-drives.

ii) the links 1 & 2(shoulder and elbow), and the sliding link attached to the link 2, will be driven by linear actuators.

iii) the winding system will be based upon a speed-controlled DC motor and a tensioner.

iv) the extensions will be added to the end of the sliding link. The length of the passive extensions will be determined experimentally upon competing and integrating the robotic arm with the chassis.

v) the material for the links 1 & 2 will be Al6061-T6. Specially shaped structures will be introduced based upon minimum-weight design.

vi) the control electronics will be allocated on the turret, not on the chassis, to provide minimum complexity of wiring.

vii) high quality slip-rings will be used for the winding system, turret and the roll joint of the wrist.

Résumé

En collaboration avec le laboratoire de robotique et d'automatisation du département de genie mécanique de l'Université de Toronto et en consultation avec la Sous-direction de l'enlèvement et de la technologie des explosifs de la GRC, la firme Engineering Services Inc. (ESI) a effectué une analyse fonctionnelle et une etude de definition du robot. L'analyse a porté en gros sur les dessins du chassis et du systeme de transmission du robot ainsi que les caracteristiques données selon les fabricants de divers composants du systeme. On s'est intéressé particulièrement aux sous-systèmes Blectroniques et de communication, à la disposition des nodules électroniques de contrôle, aux caracteristiques du systeme de transmission, à la oatterie et aux caracteristiques mecaniques du chassis et des roues. On a voulu determiner comment le bras en cours de mise au point modifierait la stabilite générale du robot. On a effectué des simulations statiques et dynamiques à l'aide du logiciel DADS. Les resultats ont servi à prévoir le comportement du robot en fonction de différentes configurations du bras. On a conclu qu'il fallait alleger le bras le plus possible afin d'assurer la stabilite du robot.

La seconde partie du projet portait sur l'étude de definition du bras télémanipulateur, la disposition des actionneurs et leurs types, des analyses de stress des articulations par la méthode des elements finis pour minimiser la masse et l'inertie, la selection des matériaux, l'étude de definition du poignet et l'incorporation du dévidoir à la tourelle et au chassis existants. L'étude de definition a été effectuée à l'aide des logiciels de conception assistée par ordinateur suivants : AutoCAD (y compris un logiciel de modelisation de solides en trois dimensions) et AutoDESIGN. Le travail analytique s'est réalisé dans un environnement Matlab. L'étude de definition était basée sur les resultats de l'analyse fonctionnelle décrite ci-dessus. Le logiciel de conception assistée par ordinateur et les logiciels mathematiques offraient la flexibilité nécessaire pour l'étude des iterations interactives multiples. Voici les principaux resultats obtenus :

i) les articulations de la tourelle et du poignet seront activés par des moteurs à courant continu et des demultiplicateurs harmoniques;

ii) les articulations n^{os} 1 et 2 (épaule et coude) et l'articulation à coulisse attachée à l'articulation n° 2 seront alimentées par des actionneurs linéaires;

iii) le dévidoir sera mû par un moteur 8 courant continu à vitesse contrôlée et réglé par un galet tendeur de courroie;

iv) des rallonges seront ajoutées à l'extrémité de l'articulation à coulisse. La longueur des rallonges passives sera déterminée experimentalement après l'integration du bras télémanipulateur au chassis;

v) le matériau utilisé pour les articulations n°° 1 et 2 sera de type A16061-T6. On se servira de structures specialement conçues conformement à l'étude portant sur le poids minimum;

vi) les modules dlectroniques de contrôle seront situ& sur la tourelle et non sur le chassis afin de faciliter le câblage;

vii) on utilisera des bagues de haute qualité pour le dévidoir, la tourelle et l'articulation de roulis du poignet.

INTRODUCTION

The explosives disposal robotic system currently under development at RCMP Explosives Disposal Technology Branch, Orleans, Ontario, in cooperation with the ESI, Toronto, represents a special robotic system that can be classified as a ***teleoperated mobile robot*** which consists of a six-wheel-vehicle, an automatic cable winding system and a modular manipulator arm. The ESI is aimed to provide the design of the prototype of both the winding system and the robotic arm. The design includes both the mechanical and electrical layouts, machining, integration and testing of the whole system.

In contrast to the existing RMI-xx robotic vehicles developed by PEDESCO Ltd., and the Miniature Remote Vehicle developed by Hovey and Associates, the new Explosive Disposal Robot (EDR) will have much ***more degrees of freedom*** and many ***new solutions and improvements*** comparing to the existing robots. The main advantages are the following:

(i) **System modularity** that allows easy disassembling and re-assembling joint modules.

(ii) Fully automatic **integrated cable winding and pay-out system** able to provide proper functioning in all circumstances including those when the vehicle makes multiple loops when moving towards a target position.

(iii) **Turret-based robot arm** with unrestricted turning ability.

(iv) **Multi-degree-of-freedom arm** (Shoulder link, Elbow link, Extension link) that allow robot end-effector to move across a large work-space.

(v) **Passive extensions** that can be mounted to the extension link to provide higher reachability in vertical configuration.

(vi) Two-degree-of-freedom **modular wrist with** a pitch and roll function. The roll angle will not be limited in order to allow infinite rotation if necessary.

(vii) **A parallel gripper** with high payload capacity will represent a separate module that can be attached to the roll-joint.

(viii) A two-degree-of-freedom modular wrist capable of carrying a NEUTREX/aiming laser/camera assembly.

The design of a robotic system having all the listed properties is extremely challenging because of the following reasons:

(a) System modularity in robotics is difficult to achieve. There are only two robots currently available with this feature. The main problem is that in the case of a modular robot it is not possible to separate the actuator from the joint being actuated. With standard robots, the actuator is nearly always separated from the joint by a transmission mechanism in order to achieve better mass distribution, i.e. to move heavy actuators towards the robot basis.

(b) Redundancy, i.e. an excessive number of degrees of freedom. Without taking into account the degrees-of-freedom of the vehicle itself, the main robot arm has 4 degrees of freedom, while each of two wrists adds two more. The total number of actuators is 9 (1 for turret, 3 for the main links, 2 x 2 for the wrists, and 1 for the parallel gripper).

The items (a) and (b) show that the complexity of the EDR is much higher than that of a typical robotic system for a similar purpose. For example, the most sophisticated RMI robot (RMI-10) has only 3 degrees of freedom (front arm up/down, back arm up/down, front right arm in/out) and a gripper.

In order to solve the problems mentioned above the work has been divided into two tasks; the System analysis and the Conceptual design. The main objectives of these two tasks were to provide precise engineering data about the parameters of existing subsystems, and to conceptualize the robotic arm by optimizing prize/performance ratio. The main objectives and solutions to the problem are outlined in the next section of the report.

The Tasks I and II have been carried out by a team of specialists over the 3-month period as specified in Appendix "A" of the contract (Section 2.2.4.). The team was composed of the following specialists:

1. System engineer,
2. Mechanical designer,
3. Stress analysis specialist, and
4. Simulation and CAD specialist.

The specialists have been selected in accordance to specific requirements of the tasks.

SYSTEM ANALYSIS (TASK 1)

The main objective of the **System analysis was to *identify all relevant parameters*** of the already designed and fabricated chassis, drive and control system. We found that the mechanical structure of the chassis and the drive system, as well as the materials being used, are selected/designed in such a manner that allows easy attachment of the robotic arm. The chassis is robust and meets stringent requirements for mobile robots being used for this purpose. In order to achieve stable behaviour of the system, the structure of the arm was carefully analyzed and interactively modified to obtain the optimum configuration in terms of geometry and mass distribution. This work has been done in close cooperation with the RCMP specialists. The volumetric working area was maximized while taking into account stability of the system. We found that the maximum length of the arm (without extensions) should not exceed more than 2 m. But, in vertical configuration it can accept extensions to allow reaching points between 3 and 5 m over the ground level. Experimentally will be determined the maximum height of the robot in vertical configuration. Some of the other parameters are listed below:

Maximum carrying capacity of the chassis at the center-of-mass is about 400 Kg.

Maximum speed of the vehicle was set to 1.4 m/sec, while the maximum speed of the robotic arm was estimated at about 0.1 m/sec.

Targeted maximum accelerations are 1 m/(sec*2) for the vehicle, and 0.1 m/(sec^2) for the robotic arm.

The maximum lifting capacity (payload) is 10 Kg.

The robot arm will be accompanied by two 20 mm NEUTREX disrupters that can be fired simultaneously.

The results of the simulation of the mobile robot are given in terms of diagrams, maximum static load at different configurations, and eigen frequencies of oscillations that can be excited by disturbances and firing the NEUTREX guns. The parameters for the simulation of the vehicle were supplied by the RCMP. The main parameters are the stiffness along the vertical axis, the position of the center of mass, and the mass of the vehicle without the robot assembly.

CONCEPTUAL DESIGN (TASK II)

The main objective of the **Conceptual design** was to determine the most convenient structure of the robot arm, type and parameters of actuators, structure and material for the main two links, sensors and control electronics concept. As pointed out, the design process involved closed-coupled cooperation between ESI and RCMP specialist in robotics design. The main objective was to achieve maximum work-space volume, stable behaviour of the system in different configurations of the arm, and minimum-complexity of the components.

The conceptual design was divided into 3 items: the design of the winding-spool and pay-out system, the design of the robot kinematics including the selection of actuators, and the minimum weight design of the two main robot links (Link 1 and Link 2).

Winding System:

The main objective was to design a minimum-height automatic horizontal winding system capable of handling both a 6 mm coax, and a 3 mm fiber-optic cable. In addition the system was aimed to perform properly in all circumstances including those when the vehicle has to perform multiple loops.

To achieve these goals, a highly sophisticated winding system was designed. It consists of a winding-spool, a slip-ring assembly between the winding spool and the turret-base, a floating arm holding an up-down reverse mechanism and an active tension-meter, a slip-ring assembly between the floating arm and the turret-base, a DC motor with a tachometer to drive the winding-spool, control electronics and custom-designed gear-sets.

The winding system can handle both types of cables with the tension in the range from 200 to 800 grams (adjustable). It fits the maximum speed of the vehicle (1.4 m/s). The slip-rings have about 10 MHz bandwidth, and very low contact impedance (milli-ohms). The coupling between the motion of the winding spool and the floating arm was minimized. The value of the coupling will be obtained experimentally upon building the prototype.

Robot kinematics:

The geometry and the kinematics of robot links were carefully studied and changed in many iterations. The robot kinematics is very important issue in this project since it determines the versatility of the robot to perform a variety of tasks in in-door and out-door environments. The optimization was performed to maximize the working area and to minimize the robot in-stability. As a result of CAD design and constant cooperation between the ESI and RCMP, we found that the most convenient structure involves 8 degrees of freedom arm:

Turret with infinite rotation about vertical axis;

Link 1 (shoulder arm) to provide pitch type of motion;

Link 2 (elbow arm) to provide an additional pitch angle;

Active extensioner (sliding joint) to provide extended reachability in radial direction;

Pitch-roll type wrist with a parallel gripper;

Pitch-roll type wrist (parallel to the gripper-wrist) to allow mounting of disrupter assembly

This kinematic structure was obtained after several iterations by taking into account the drive units and the maximum payload. The main reason for selecting the jaw-pitch-pitch structure of the first 3 joints is to achieve maximum volumetric operational space of the robot. The lengths of the links 1 and 2 are selected in such a manner to allow the robotic arm to reach the ground level close to the chassis and to be compatible to the linear actuators available. A careful study of geometry lead to the proper selection of angular limits for every degree of freedom: 0 to 110 degrees for the first two pitch joints, and from -120 to 120 degrees for the wrist-pitch joint. Turret and the wrist roll joints have no limitation in angles.

The angular limits were highly influenced by the type of actuators: rotary actuators have no severe restriction in angular motion, while the linear actuators driving rotary joints have a theoretical limit 180 degrees. The linear actuators are selected for two main links: Link 1 and 2. The reason is heavy load on these two joints. Having in mind that the fully extended robot arm is about 2 m long, and that the double-wrist load exceeds 50 Kgf, it is clear that the torques to be applied at two main pitch joints are very high and require powerful rotary actuators able to deliver torques as large as 1000 Nm. The weight of such motor/gear assemblies would be large and would probably require special transmission system. To avoid this problem, it was necessary to consider linear actuators to drive the main pitch joints. A detailed study of static forces discovered that the forces acting along the actuators (“dynamic force”) are in the range from 2000 to 7000 N depending on the robot configuration and the joint itself.

We selected special high-quality ball screw SKF actuators. The Ball screw assembly provides‘smooth motion with very low friction, giving the complete actuator a high level of efficiency. An additional worm gear is used to provide high gear-ratio to the actuator. Since the maximum dynamic load of these actuators is 6000 N, we have selected two actuators per joint. This concept will not only reduce the load force, but provide balanced load to the links and smooth motion of the end-effector.

Minimum Weight Design

The selection of the shape of two main links (Link 1 and Link 2), the openings, and the material being used, is facilitated by the use of finite-element stress analysis, optimization and the expert system within the AutoDesign environment. These two links were designed as quadratic tubes with linear actuators entering the interior space of the links. For this reason, the upper and lower sides of the tubes are not completely covered. Since the stress within these two plates is low (there is no gravitational load in lateral direction), we focused the analysis on the two side-walls of the links. Since these two plates are equally loaded, we reduced the analysis to a single plate with an equivalent load equal to the half of the total load at the end-effector. Being able to reduce the analysis to a planar problem was very beneficial in terms of computing time. That allowed sophisticated optimization of the shape, openings, and material. The material selected is Al 6061 T6 with the yield stress 40.000 lb/in^2, and tensile stress equal 45.000 lb/in^2. Similar analysis has been done for the first link (less critical case). The safety factor is extremely large and is between 3 and 4, still yielding very low mass of about 1 kg per plate. Since the weight of actuators is about 3 Kg, the total weigh of the link 2 (without the additional sliding joint) will be about 6-7 Kg. The sliding joint will add about 4-5 Kg to the weigh of the second link. The estimated total weight is thus about 10 to 12 Kg, which is much less than the weight of the wrists (with barrels, gripper, etc.).

PLAN OF WORK AHEAD

The work to be done within the Tasks III and IV is well ahead of the plan. The work on Winding and Pay-Out system has been done in parallel to the Tasks I and II. Several designers have been contributing to the design of the winding system. The work is expected to be completed at the end of March, 1994.

The cost of some components, especially the slip-rings, is much higher than estimated (a single slip-ring costs about USS 5,000). In addition, the system was designed in several iterations in order to meet stringent requirements in terms of the allowable height of the unit. Excessive efforts have been made to fit into the budget allocated to this project.

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CONCLUSIONS

The ESI team in consultation with the RCMP Explosives Disposal and Technology Branch specialists has completed the system analysis and conceptual design of the Explosive Disposal Robot (EDR). The system analysis includes the study of engineering drawings of the robot chassis and drive system, while the conceptual design involves the study of the geometry of the robot, kinematic parameters, disposition and types of actuators, finite-element stress analyses of links to minimize the masses and inertias, selection of materials, conceptual design of the wrist and the winding & pay-out system, and its integration with existing chassis and turret. The amount of work exceeded significantly the predicted one. The results are very encouraging and are opening a new area in modern robotics related to the design of teleoperated mobile systems. ESI is confident that the EDR robot will bring Canada to the front line of current technology and will surely contribute to the competitiveness of Canadian economy.