Image Cover Sheet

CLASSIFICATION UNCLASSIFIED	**SYSTEM NUMBER** 513876

TITLE

Physical Simulation of Weight Loss in Shoulder-Supported Rocket Launching

System Number:

Patron Number:

Requester:

Notes:

DSIS Use only:

Deliver to:

This page is left blank

This page is left blank

Physical Simulation of Weight Loss in Shoulder-Supported Rocket Launching

J.J. Grodski† and **B. Hall**‡
†Defence and Civil Institute of Environmental Medicine
P.O. Box 2000, Toronto, ON, Canada, M3M 3B9
Email: jul@dciem.dnd.ca
‡B Hall Industries Inc.
146 McAllister Road, Toronto, ON, Canada, M3H 2N7

ABSTRACT

Rocket launching from shoulder-supported systems produces a jolt associated with the change of the launcher mass and weight when the rocket exits the tube. The effect is therefore central to the design of shoulder-supported rocket launcher simulators. An advanced design model of a physical weight unloading simulator has been developed to simulate operation of Javelin, an air defence weapon in use by the Canadian Forces. The developed concepts and systems, however, can be generalized and adapted to facilitate similar training requirements with other shoulder supported systems. The simulator is based on the use of the RObotic Muscle-like ACtuator (ROMAC) to achieve the weight unloading effect at the shoulder and arms of the operator. It has a ceiling-mounted overhead gantry X-Y table servo system that delivers precise unloading action independent of the operator's position/orientation. It allows operator movement within a large 100 ft^2 area and it keeps the lifting cable vertical. The system offers rapid response and high fidelity unattended operation.

KEYWORDS

training simulators, physical simulators, weight unloading, muscle-actuators

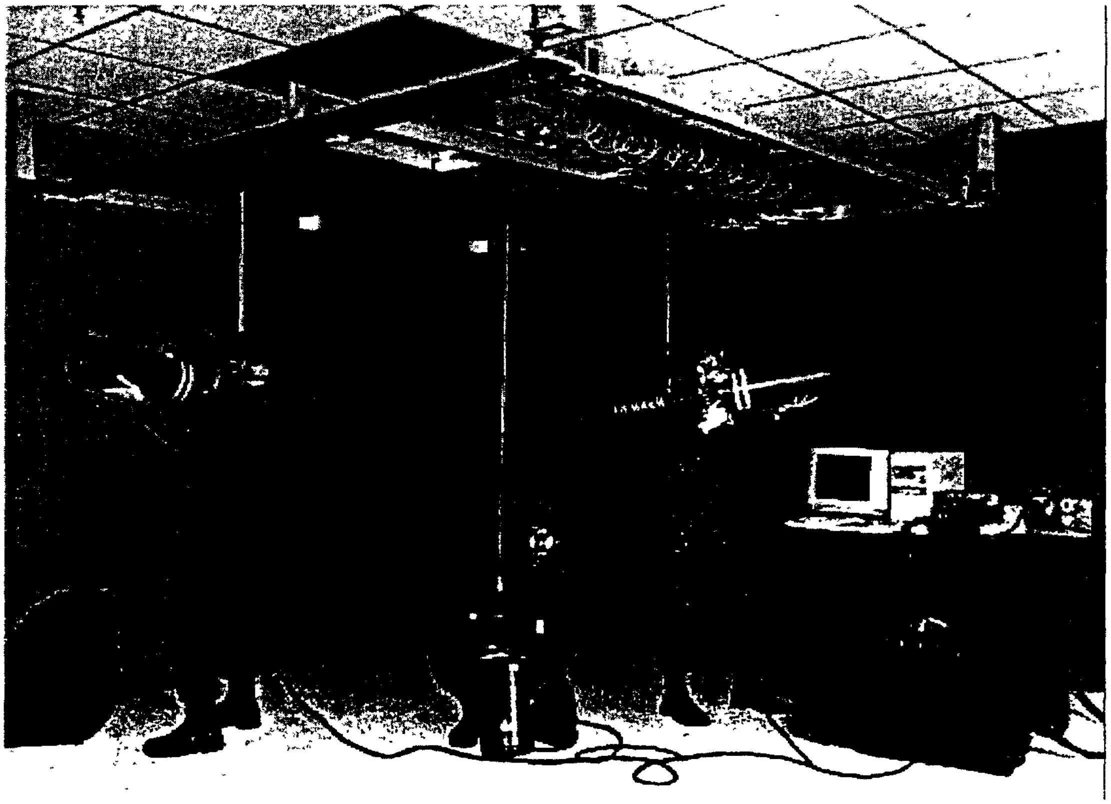

Figure 1. The overall view of the ceiling-mounted Javelin physical simulator of weight loss with an operator in the ready-to-mount position, showing weapon's top view including the string attachment, and in two different firing orientations.

INTRODUCTION

Shoulder-fired guided missile systems are an integral part of modern defence operations. The effectiveness of these weapons is related directly to the quality of the training the operators receive. Live firing of these weapons provides optimal training experience but is prohibitively expensive. It is therefore used only as a final stage in an extended training program based on the use of physical simulators. Effective simulators for shoulder-supported launchers need to reproduce the physical, visual and aural aspects of real systems. This paper focuses on the physical interaction between the weapon and the operator. Given that a missile may weigh as much as 28-lb, the launcher's weight and center of gravity change dramatically the instant the rocket/missile leaves the launch tube. The rapid loss of weight creates the problem of a transient operator and tube motion which equates to a perturbation in aiming. This directly affects the aiming of the missile in a bore-sighted guided missile. In a sight-stabilised system, the sudden physical jolt serves to break the operator's concentration, hindering the aiming/delivery procedure. Therefore, it is essential to have a realistic physical unloading feature built into the simulator to prepare the operator for the jolt. An operator who had experienced the physical aspects of firing many times in such a simulator has a better chance to develop a steady, unflinching ability to aim and deliver the rocket to the target. In order to make the operation realistic throughout, it is also essential that the weapon is in its lightened state for the dismounting from the shoulder and putting it down to ground.

ROCKET LAUNCH CONDITIONS AND EFFECTS

Operator training for shoulder-supported rocket launchers is of high importance due to the lethality of the circumstances of their use. In practice, the operator would only have one opportunity to make the shot successfully or suffer dire consequences. The pressure to achieve a successful shot is compounded by the nature of a shot. Typically, the flight of the missile is only seconds in duration. For the first second or two the operator is recovering from a startle reaction caused by the noise of the initial rocket propulsion blast, feeling the effect of the sudden weight loss from the missile leaving the launch tube and back blast from the missile. This can mean that the operator is left with only a second or two to consciously guide the missile. The loss of the missile weight from the operator's shoulder causes a physical movement of the launch tube which in turn causes a movement of the target scenery that the operator is viewing. In a bore sighted missile system it also causes a movement of the cross-hairs or aiming point, potentially also mis-guiding the missile for some duration before the operator re-steadies himself. If the initial deviation is too large or lasts too long it is possible that not even the best aiming skills would be sufficient to regain an accurate missile trajectory in time to hit the target. Thus the operator's a priori preparation for the short instant of launch is critical to the success of the shot.

There are multiple physical launch effects that the operator experiences. One effect is a recoil-like effect caused by a few factors. The rocket is held in relatively snug, precise alignment prior to firing, implying there is some static friction to be broken before the rocket can start sliding out of the tube. This creates a short forward tube kick. This is followed by a back-kick as the launch tube is caught by the blast of the second stage of the rocket. The operator also experiences the wind of the back blast and the debris it carries impinging on his person. In some missiles, an initial spin can also be attained which can exert a short axial torque pulse on the tube. However, the largest direct effect is the loss of weight that the operator is supporting. It is a dramatic change because the missile weight can exceed 60% of the system weight.

Before firing, the 28-lb missile is distributed between the operator's shoulder and arms, biased more onto the shoulder. The instant after firing a combination of factors creates the launch tube motion. First, the operator's shoulder and arm muscles are still exerting an upwards force sufficient to support the previously full launch tube, as physiologically there has not been enough time to adjust to the nearly instantaneous loss of the weight. Second, the lightened load of the now-empty launch tube also has a much smaller inertia, so the operator's applied muscular force begins to accelerate the tube upwards. Any amount of equal upward motion by the arms and shoulder causes a net translation of the launch tube, resulting in a small shift of the cross hairs and target scene seen by the operator. This is a relatively small effect. The second factor is that any inequality of shoulder and arm movement causes an aiming-wise elevation deviation. Due to the large distance out to the target, tiny elevation-wise rotations of the launch tube cause a large movement of the target scene seen by the operator. This is a large effect.

The load loss on the arms and shoulder of the operator does not create a purely vertical motion in the operator. Vertical and horizontal motions in a human are coupled by geometry and by compliance of musculature. For example, a person's shoulder moves in an arc and a sudden load change on the shoulder typically propagates into motion of the spine, hips and legs as well. This nature of human reaction combined with the asymmetric position of the launcher with respect to the operator's body gives reason for weight loss and other smaller physical forces to result in interacting vertical and horizontal perturbation motions of the launch tube. The physical simulator provides the means for the operators to experience these perturbations and acquire experience to be able to deal with them effectively.

WEIGHT UNLOADING TRAINERS

The weight loss is the most significant effect impinging on the effectiveness of the operator of a shoulder supported launcher. Although there are also other effects which impact the operator, his/her ability to train to overcome the weight loss is paramount. It is for this reason that simulators/trainers for these operations aim to address the weight loss issue as the primary problem. Various solutions were implemented in existing weight unloading trainers. The primary examples are discussed below.

Single Weight-Dropping Device

A recoil force and weight loss device for simulation of bazooka firing[1] used pneumatic actuation to achieve the two goals. The weight dropping was achieved by discharging a pneumatic actuator which maintained it in a "loaded", pre-firing state. It can be expected that the weight dropping was less than instantaneous. Also, the weight was mounted on an arm with a large offset, creating unnatural constraints and large inertia effects. The devise must have been cumbersome in use.

Cable Pull-Down Device

One existing force loading method used an empty launcher configuration with a pair of ropes attached near the front and rear of the tube that applied a downwards force load equal in size to the missile weight prior to simulated launching. The rope tension was released at the instant of firing. The operator had to be positioned very precisely as each rope was required to go down vertically to a fixed position on the floor. Sideways deviation from the position caused net sideways force load on the launch tube and hence the operator. Front to rear operator position deviation from the ideal location similarly caused unbalanced net loading. Finally, any sideways aiming error between the launch tube and the direction formed by a line between the two rope fixation points on the floor created a net torque on the operator. Hence, extra care was required to properly align the operator for each shot, detracting from the need for concentration on the aiming. Neglecting the alignment issue resulted in improper training for force loading.

Two-Weights Dropping Device

Another method used an approximation of an empty launcher which had two weights, one at the front and one at the rear of the launch tube, that were released at the instant of simulated firing. The sum of the two weights was made approximately equal to the weight of the missile, but the launch tube ended up overweight because of the practical necessity of weight holding/release mechanisms that were not present in an empty launch tube. The problem with this method was that the falling weights were of substantial size and posed a danger of striking the operator. Weight-catching baskets impeded and distracted the operator. Additional personnel were needed to adjust the positions of the baskets when the operator was performing a simulated shot. The oversized empty launcher inertia of the configuration slightly affected the accuracy of the transient tube motion perturbation upon firing. The required reloading of the weights for each shot was an inconvenience. In summary, the weight dropping method overcame the operator movement restriction imposed in the cable pull-down method but it also had significant deficiencies.

Force Generation (lifting) Device (FGD)

The FGD apparatus takes a different approach. It starts with a loaded launch tube and it creates the weight unloading effect by lifting the tube vertically at the instant of simulated firing with a force equivalent to the weight of the missile leaving the launch tube. A prototype portable FGD system with an overhead gantry allowing movement within 2'x2' area was described earlier.[2]

RObotic Muscle-like ACtuator (ROMAC). The lifting force is generated in this design using a ROMAC actuator[3,4] which is particularly well suited for this application. The actuator is a pneumatically-operated, single-acting, articulated polylobe bladder with a flexible, non-elastic sheath construction which expands in volume and contracts in length during pressurization. The ROMAC actuator offers rapid response, light weight and no air leakage vs. friction problem. It has a very slight force vs. stroke hysteresis. The force characteristics of a 4" ROMAC are shown in Figure 2 and illustrate the typical high forces developed at low contractions with relatively low pressures. ROMAC tension is proportional to pressure for a given contraction.

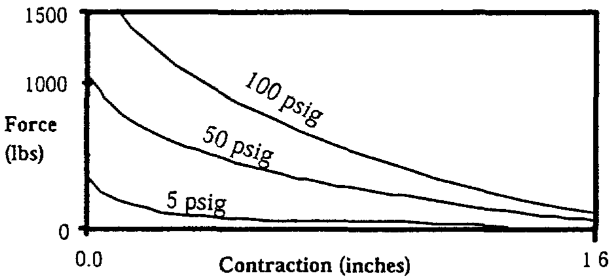

Figure 2. ROMAC Force vs. Contraction Characteristics at Constant Pressure

For the system with a 28-lb missile, there was a clear mismatch between applying a 28-lb lift force and using an actuator capable of over 1000-lb to do it. This necessitated a 6:1 stroke and tension conversion mechanism, shown in Figure 3, which resulted in the use of the 168-lb constant tension characteristic of the ROMAC shown in Figure 4. The mechanism is essentially an inverted use of a classic block and tackle.

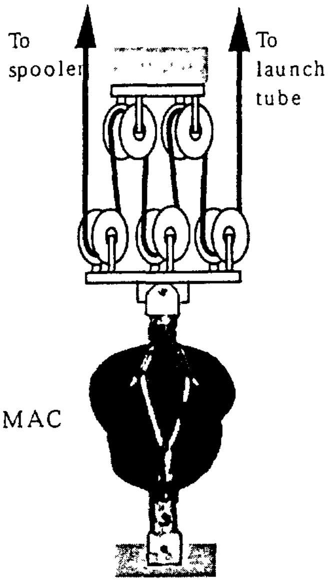

Figure 3. 6:1 Stroke Multiplying and Tension Dividing Inverted Block and Tackle Mechanism with ROMAC

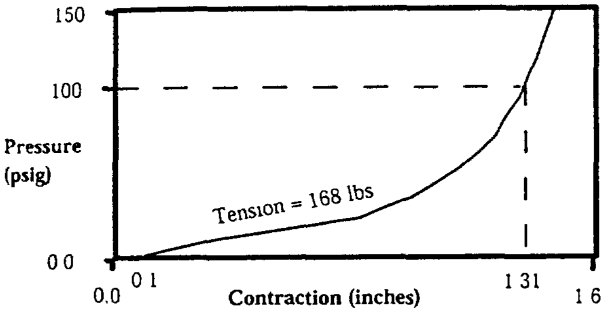

Figure 4. ROMAC Constant 168-lb Tension Characteristic (used to create 28-lb cable tension with inverted block and tackle mechanism).

The constant tension characteristic shown in Figure 4 illustrates that not all of the ROMAC stroke can be used. These limitations are defined by the maximum and minimum inflation pressures available for the ROMAC. In Figure 4 a maximum pressure of 100 psig allows a maximum contraction of 1.31", beyond which either more pressure would be required or the cable tension would drop below 28-lb. At the other end of the stroke range, low contractions result in a very long, extended ROMAC casing shape which begins to exhibit its own mechanical forces. At approximately 0.1" contraction the mechanical forces alone equal 168-lb with zero applied air pressure. The zero contraction point was defined to be the contraction point at which 200-lb of tension occurred with no applied air pressure. Thus for FGD operation the allowable vertical movement was six times greater than the allowable ROMAC stroke, or 6 x 1.21" equalling about 7.25". This amount was deemed sufficient to account for vertical translation of the simulator launch tube during a typical firing. The launch tube essentially stays in the same location, that being on the operator's shoulder during a firing. In reality the inverted block and tackle is arranged so that the ROMAC travels to near the middle of its allowed stroke range upon firing. Details of the actuation during firing were discussed earlier[2].

In the ROMAC-actuated FGD, the actuator pulls on a cable which is attached to the mock-up of the missile launcher held by the operator. A take up motor and cable spooling system provide a constant (token) line tension prior to ROMAC activation. At the same time, an x-y table gantry servo system keeps the lifting cable vertical within a 10'x10' area in preparation for the instant of firing. This allows the operator to comfortably adjust his position on the floor in any direction. When a simulated "launch" is initiated, the spooling system is isolated using a fast-acting brake, and the ROMAC actuator is activated to exert a constant line tension simulating a loss of weight of the missile. By having only a single cable attached to the top of the simulator launch tube assembly, the system also allows the operator to aim anywhere within the 360° horizon and at the same time aim upwards into the sky, if desired. The system has the further advantage that operator involvement is limited to actions associated with the operation of the weapon and that there is no need for assisting personnel

The system was designed for use in a permanent training facility, such as a Javelin Detachment Trainer. The large, 100 ft^2 working space that it offers is ample for simulation of any operational scenario and for concurrent training of complete detachments as there are no interfering floor-mounted structures. It also accommodates any height allowed by the structure of the building.

The known deficiency of the system is that there is still one cable attached to the simulator launch tube and that the motion perturbation resulting at the time of weight loss is incorrect to some degree. The lift cable, however, is relatively unobtrusive. The motion perturbation is slightly incorrect because while the lift cable, operator's shoulder and arm forces are correct, the inertia of the simulator launch tube is incorrect. This is because although its apparent weight to the operator after firing is correct, it still contains the concentrated mass at the location where the center of mass of the real missile would normally be.

Other Actuation Schemes. Other actuation alternatives, including electrical motors, simple mechanical and pneumatic cylinders for creating lift force were assessed earlier[2]. They have been found to offer less attractive solutions for the weight unloading problem. Nevertheless, a solution involving an electric motor winding the lift cable onto a drum is quite feasible. However, this approach would involve high electric power requirements and significant potential for runaway types of failure. In contrast, the limited ROMAC lift stroke insures safety because it does not allow for the potentially unlimited upward lift distance of an electric motor in a failure condition.

CABLE SPOOLING PRIOR TO FIRING

In the initial stages of a shot where the operator is lifting the launcher to his shoulder and taking aim on the target, the FGD system has the two tasks of managing the lift cable and keeping the cable lift point directly overhead. The success of keeping the lift point directly overhead depends on maintaining the cable partially tensioned so that it forms a straight line between the lift point and the launch tube. The cable tension used to do this, however, was small enough that the operator would not notice it. An adequate tension for that purpose was 0.1 to 0.2 lb. The spooler cable take-up capacity was made adequately large enough to cover the difference between setting the launch tube on the floor and setting the launch tube on the shoulder of a tall operator. The spooling feature allowed the FGD to naturally self-adapt to any height of operator.

The spooling requirements for the instant of firing were also identified. One was that a nearly instant lockup of the spooler could occur without slipping while structurally withstanding the 28-lb force. Another consideration for the spooler at the instant of firing was that multiple layers of loosely wound cable could tighten in on themselves upon experiencing the higher tension, with the top strands forcing themselves down in between the looser layers underneath. This would have caused two negative effects. First, the cable would have been wedged and jammed when returned to low tension spooling, interfering with proper operation. Second, the process of the cable wedging in on itself would have represented a soft, mushy anchor point from which to generate a rapidly rising 28-lb cable tension force.

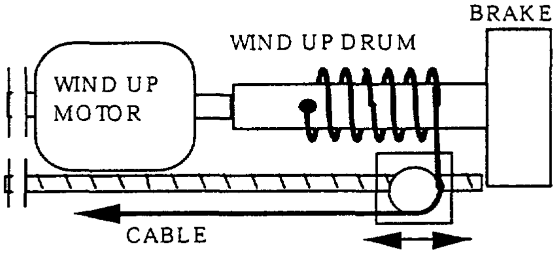

Figure5. Single Cable-Layer Take-up Spooler with Brake

This suggested the use of a cable layup guide, but another effect discouraged that. The effect was the relative sizes of the cable bending and guiding friction forces compared to the very low tension set point; they were almost equal. In particular, the friction of spinning the spooling motor and windup drum itself was significant. Thus great efforts were taken to reduce friction so the low cable tension fidelity could be maintained. The desired design solution was to make the spooler so the windup drum incremen itself sideways per wrap of cable, using a lead screw ty of approach. Space constraints, however, required tha layup-guide pulley be used as shown in Figure 5 with associated slight friction contribution. This resulted i single layer cable winding. The layup mechanism had be optomised for minimal friction contribution to spooler drive train to minimise loss of spooli performance.

The control method used to perform the low tensi spooling was a combination approach The ba principle of a DC motor's torque being proportional to armature current was utilised in a feed-forward fashion. constant current was applied which would have idea created the correct spooling tension if friction neglected. In addition, a feedback loop was used wh the cable tension measuring cell at the overhead lift po was read and used to create an error signal which added to the feed-forward signal. This addition grea improved the fidelity of the low spooling tensi canceling much of the pulley friction between the wind drum and the cable tension sensor. The cable tension the operator was of better fidelity mostly due to the f that the cable tension sensor was at the last pul traversed by the cable. A similar accuracy benefit gained by the post-firing ROMAC tension servo beca it also used the overhead tension sensor.

A co-feature of spooling is the capability of controll brake slippage which allows the tube to be lowered floor in a lightened state in a typical post-fir maneouver. When lowering, the operator would require high tension fidelity, so the brake was modula to allow slippage at slightly higher than 28 lbs tensi thus maintaining lockup at the normal 28 lbs tension. controlled brake-slippage feature cooperates to prese the ROMAC limited-lift safety attribute by letting system be lowered but contributing to any possibility uncontrolled excessive lifting during a potential hardw failure mode.

OVERHEAD LIFT-POINT X-Y SERVOING

The X-Y servoing was done to keep the cable lift pc directly above the operator such that the lifting cable vertical. The cable attachment point on the tube directly above the concentrated weight, which was pla where the C of G of the real missile would have be Thus the lifting force vector would directly line up w the gravitational force vector of the concentrated mass the simulated missile inside the tube, allowing compl cancellation of the weight of the "missile".

The mechanism for X-Y positioning was a rectang frame which had two carts as shown in Figure 1. small cart contained the actuator with the str multiplying and tension dividing mechanism, cable spooler with brake and all related electronics. The cart moved on wheels along the long beam of the large cart. The large cart moved on wheels along the outer frame in a direction perpendicular to the small cart track Timing belt drives operated by electrical motors provided the controlled mobility function for both carts. Both ends of the large cart were driven using a mechanically coupled drive so that it stayed aligned in the frame in-spite of its large size. Transmission of signals, power and delivery of the compressed air between the carts and the frame was done using coiled houses and multi-conductor cords.

The angle of the string with respect to the frame was directly measured at the small cart by separate X and Y angle component sensors. Assuming the launcher to be in its desired location, each cart separately servoed its position to minimise its component of the string angle. Because of the servoing action, operator movements were continually tracked. The servoing feedback loop used proportional and integral action. The integral action was used to attain as close as practically possible to zero error, once the operator settled into a firing position.

The overhead frame was designed to allow for its levelling during installation to the ceiling structure. This was essential to provide reliable X-Y servoing and vertical lift. The frame was designed with excess strength and rigidity such that negligible deflection resulted when the sudden lift force was applied.

OTHER SUBSYSTEMS

The system also encompassed an interface package for interconnection of the simulator with power and compressed gas sources in the building. A computer was used to correlate the trigger, lift and sound and to generate the acoustical signature delivered by a large speaker in an exact phasing, just as it would take place during live firing of a Javelin missile. An acoustical signature played during the firing was acquired from live firings and it aimed to provide a realistic background and cues to the operator in the evolution of the firing event.

ROMAC OPERATION AND CONTROL DURING A FIRING

The fast acting ROMAC actuator was used to create the cable lift force via the stroke multiplication and force division inverted block and tackle mechanism at the instant of simulated firing. The result of this was that the ROMAC exerted 168-lb independently of its stroke or contraction by having its internal pressure varied according to the graph of Figure 4. The pressure change was attained by using a precision proportional, fast acting servo valve to add or exhaust compressed air to or from the ROMAC based on the measured tension from the overhead lift point cable tension sensor.

A basic feedback algorithm with valve aperture size set according to proportional and derivative feedback of the cable tension error was used. An additional signal, the velocity of the stroke of the ROMAC, was used as a kind of feedforward, prediction of air flow requirement control signal. The tuning of the control gains was done empirically to result in an essentially critically damped response to the step tension command. The critically damped response was an approximation to the weight loss vs. time waveform from a real firing. A simplified summary of the tension rise waveform suitable for practical purposes was that the operator experienced the weight loss of the real missile over the time duration of the missile leaving the tube, yielding a tension rise time as a general control tuning criterion. In reality a variation of the simplified criteria was required to attain good lift force control system tuning, described earlier.[1]

CONCLUSIONS

The ceiling mounted physical simulator delivers the means for effective training of operators for shoulder-supported rocket launching of the Javelin, air-defence missiles. It features very accurate weight loss simulation synchronized with the firing cycle initiated by the trigger actions of the real weapon. It also offers freedom to train in a large area, permitting unobstructed training of Javelin detachments. ROMAC actuators proved to be particularly suitable for use in the lifting FGD apparatus of the simulator. ROMAC characteristics modified by the stroke multiplying and tension dividing inverted block and tackle mechanism provide an excellent match to the need of the lifting FGD apparatus. The self-limiting nature of the actuator also provides an inherent safety feature for the FGD system, precluding occurrence of any run-away conditions.

REFERENCES

[1] P.D. Grimmer and E. Swiatosz, Recoil Force and Weight Loss Simulator Device;1982,US Patent 4,321,043.

[2] B. Hall and J.J. Grodski, Force Generation Device for Simulation of Shoulder-Supported Rocket Launching; in Proc. Robotics and Knowledge Based Systems Workshop, Canadian Space Agency, St. Hubert, PQ, Canada, 1995, pp.365-372.

[3] J.J. Grodski and G. B. Immega, RObotic Muscle ACtuator (ROMAC) Theory; in Proc. DREP/RRMC Military Robotic Applications Workshop; Victoria, B.C., Canada, 1987; RRMC Special Report 87-1, pp.41-48.

[4] B. Hall and J.J. Grodski, Basic ROMAC Control Algorithms; in Proc.of the Knowledge-Based Systems & Robotics Workshop; Ottawa, Canada, 1993; Dept. of National Defence Canada, pp 701-708.

513876