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A Low Cost Parallel Robot and Trajectory Optimization Method for Wrist and Forearm Rehabilitation using the Wii

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***Abstract*—A robot called the Closed-chain Robot for Assisting in Manual Exercise and Rehabilitation (CRAMER) was developed to assist impaired persons in making three degree-of-freedom movements of the forearm and wrist (forearm supination/pronation, wrist flexion/extension, and wrist ulnar/radial deviation). With a parts and machining cost of less than $1500, this robot was designed to be inexpensive by using a simple parallel mechanism design and off-the-shelf hobby servomotors. CRAMER is intended to engage patients in their rehabilitation therapy by having them play computer-based exercise games. Toward this goal, the remote for Nintendo's Wii was integrated into the handle of the robot in an attempt to allow patients to play the high-quality yet affordable motion-based games that have been developed for the Wii. A framework for planning robot joint trajectories capable of generating desired accelerometer measurements used by Wii games was developed using function optimization techniques. Results of a preliminary experiment with the bowling and golf games of Wii Sports show the feasibility of playing Wii using robot-assisted wrist movements. However, to make this approach clinically practical, an improved software communication with the Wii would be necessary.**

***Index Terms*—wrist, stroke, rehabilitation, robot, video games, Wii, acceleration, optimization.**

I. Introduction

STROKE is the leading cause of disability in the United States. More than 4.7 million Americans are currently living after experiencing stroke, of which at least 1.1 million report difficulties in performing activities of daily living (ADLs) [1-3].

Repetitive movement therapy has been proven to reduce impairment in chronic stroke patients [4, 5]. However, the gains are often small, and physical therapy is labor intensive and expensive. In order to try to increase gains by giving patients more repetitive therapy at lower cost, many research groups and companies are developing robotic devices to aid in the rehabilitation of chronic stroke patients [6].

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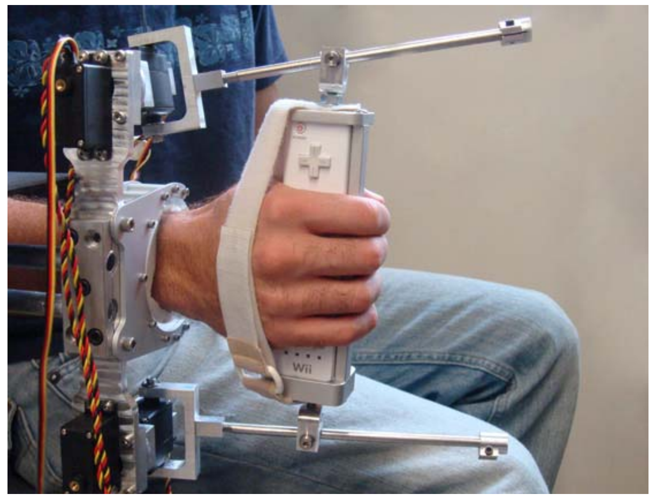

Fig. 1. The CRAMER robot with a healthy subject.

Robots have been used for both upper and lower extremity post stroke rehabilitation. However, many of the upper-extremity rehabilitation robots, such as ARMin [7], Pneu-WREX [8, 9], and GENTLE/S [10], lack the ability to assist in wrist and forearm motions. Some devices, such as the BiManuTrack [11], an extension to the MIT-MANUS [12] and the RiceWrist [13], have been designed specifically for the rehabilitation of the forearm and wrist. The latter two robots allow for 3 degree-of-freedom (DOF) motions of the forearm and wrist, but are relatively expensive and large. Other robots, such as the Hand Mentor [14] and HWARD [15], have been built to extend the wrist and open the hand, but neglect forearm rotation and wrist radial/ulnar deviation. Overall, current devices that incorporate wrist actuation are either expensive, bulky, or lacking in range of motion [16]. We designed a device to address these problems.

II. Design Description

The Closed-chain Robot for Assisting in Manual Exercise and Rehabilitation (CRAMER) uses a parallel mechanism to assist in 3 DOF wrist and forearm exercises (Fig. 1). The 3 DOF allow for wrist flexion/extension (F/E), radial/ulnar deviation (R/U), and forearm supination/pronation (S/P). The parallel design allows for lightweight construction of the robot, which is desirable for mounting onto arm

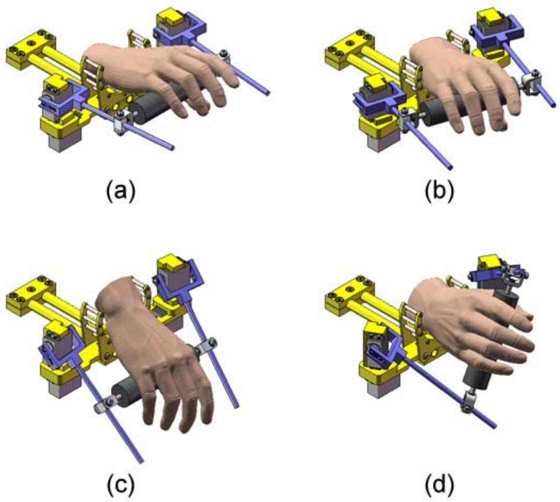

Fig. 2. 3D renderings of CRAMER showing (a) the neutral position, (b) ulnar deviation of the wrist, (c) wrist flexion, and (d) forearm supination. The orientations of the guide rods determine the wrist orientation.

rehabilitation robots and for portability.

Wrist actuation is achieved through controlling the position of the handle of CRAMER with two guide rods (Fig. 2). Each guide rod can be commanded to point in a desired direction using two highly geared hobby servomotors connected in series perpendicular to one another at the base of the rod. When the motors are given desired angles the guide rods start to move to point in their desired directions. As the guide rods move, the ends of the handle are free to slide along them, but tend to move in the directions that reduce the axial forces on the handle causing it to slide into a desired orientation. One drawback to this setup is that if the frictional forces created by the ends of the handle sliding along the guide rods are large, the robot can lock. With only plastic sheath bearings, however, we found we can produce motions up to 1 Hz without experiencing lockup.

Translational motions of the wrist are constrained by a rotating cuff. The cuff is designed to allow for S/P rotations and is positioned behind the wrist so that it does not impede F/E or R/U rotations. A Velcro strap is used to help secure the hand to the handle. These constraints are important for ensuring that a given handle orientation results in a unique wrist configuration.

The Hitec HSR-5995TG are the inexpensive, compact, high-torque servomotors used in CRAMER. Chosen for the aforementioned qualities, these motors are capable of 3 N·m (2.2 ft·lbs) of torque, but only weigh 62 g. The total weight of the device with these actuators is about 1.5 kg (3.3 lbs). While only capable of speeds up to 8.5 rad/s, these motors are fast enough for simulation of most wrist motions used in ADLs. These servos are internally position controlled with the desired position given through a pulse code modulation scheme.

III. Device Kinematics

The first calculation towards solving the kinematics of this device was to calculate the number of DOF. Spatial parallel mechanisms like CRAMER can sometimes have unintuitive DOF, and we wanted to confirm that the device had 3. The Kutzbach-Gruebler equation for spatial mechanisms [17] was used for calculating the DOF of CRAMER. This equation can be written

$$DOF = 6(\ell - j - 1) + \sum_{i=1}^{j} m_i \,, \tag{1}$$

where ℓ is the number of rigid links that make up the mechanism, j is the number of joints, and m_i is the mobility of the i^{th} joint. We carried out this calculation using the schematic in Fig. 3 and confirmed that CRAMER has 3 DOF.

Next we solved for the relationship that allows us to compute the angles to which the motors need to move in order to cause the wrist/forearm to have a desired configuration. We started by deriving the equations that compute the locations of the ends of the handle as a function of wrist/forearm angles. Using a product of exponentials framework [18], we can calculate the location of any point rigidly attached to the hand with

$$P(\theta) = e^{\hat{\xi}_S \theta_S} e^{\hat{\xi}_R \theta_R} e^{\hat{\xi}_F \theta_F} P_0 \,, \tag{2}$$

where $P_0 \in \Re^4$ is a 4-dimensional representation of the location of the point before undergoing any rotation, θ_S is the S/P angle, θ_R is the R/U angle, θ_F is the F/E angle, and the $\hat{\xi} \in \Re^{4\times4}$ are the corresponding partial twist matrices of the rotations.

Now we solve for how to move the motors so they orient the guide rods through the points on which the handle ends should lie. Fig. 4 shows how the motors control the guide rods. Letting A be the location of the top intersection of the axes of the motor pair, B be the location of the top end of

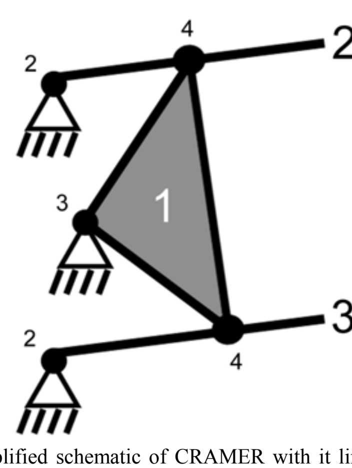

Fig. 3. Simplified schematic of CRAMER with it links numbered and joints labeled by mobility. The ground makes up the fourth link.

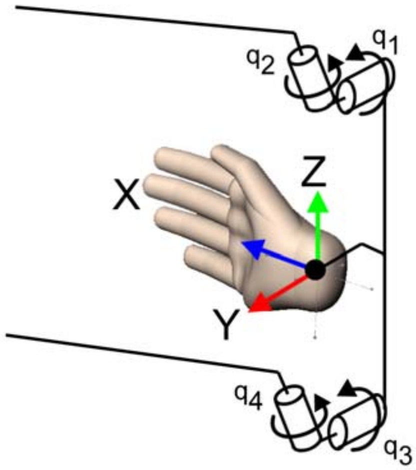

Fig. 4. Simplified schematic of how the motors configure the guide rods. The hand is in its home position.

the handle, C be the location of the intersection of the axes of the bottom motor pair, and D be the location of the bottom motor pair, the motor angles can be solved as:

$$q_1 = -\arctan\left(\frac{B_z(\theta) - A_z}{B_x(\theta) - A_x}\right), \tag{3}$$

$$q_2 = \arcsin\left(\frac{B_y(\theta) - A_y}{\|B(\theta) - A\|}\right), \tag{4}$$

$$q_3 = -\arctan\left(\frac{D_z(\theta) - C_z}{D_x(\theta) - C_x}\right), \tag{5}$$

and

$$q_4 = \arcsin\left(\frac{D_y(\theta) - C_y}{\|D(\theta) - C\|}\right). \tag{6}$$

Equations (2)-(6) can be used to calculate motor angle as a function of the wrist/forearm angles.

Using actual values for A, B_0, C, and D_0 measured from the robot and taking into consideration the ranges of motion of the individual servos as well as the minimum and maximum positions on the guide rods between which the ends of the handle can lie, we determined the range of motion (ROM) of CRAMER. These values were then verified with the actual device with a ball-joint simulating the wrist and have been summarized in Table I. Cramer's ROM matches the human forearm/wrist ROM well, except providing slightly less than desired R/U rotation. Lengthening the guide rods by about 10 cm (4 in) would have eliminated this issue, but we were concerned about them hitting into any nearby objects or people.

TABLE I
RANGES OF MOTION.

	CRAMER	Wrist Range of Motion Used in ADLs
S/P	85°/-90°	85°/-85°
R/U	10°/-15°	50°/-40°
F/E	90°/-70°	55°/-60°

Angles for CRAMER were measured with respect to the home position shown in Fig. 3 using a ball-joint to simulate a wrist. The angles used in ADLs are obtained from [19, 20]. The range of motion of CRAMER depends on the distance between the center of a subjects grip and the placement of the cuff on their wrist. The numbers here are for a relatively short distance. As the distance gets longer the range of R/U increases, but the range for S/P will decrease. The placement of the cuff has little effect on the range of F/E.

IV. TRAJECTORY PLANNING FOR ACCELERATION-BASED VIDEO GAMES

For initial testing of CRAMER, we explored the possibility of using the robot to assist patients in playing games for Nintendo's Wii. We were attracted to this possibility because considerable resources have already been invested in making low-cost, graphically sophisticated, engaging games for Wii, Having affordable and motivating games is desirable for implementing repetitive practice by stroke patients. Unfortunately, however, existing Wii games are often too difficult for people with moderate to severe movement impairment after a stroke to play. We hypothesized that CRAMER could assist patients in making the movements necessary to play the Wii games with their forearm/wrist alone, instead of their whole arm.

To test this hypothesis, we needed a method by which CRAMER could reproduce the motions that are used to play games for Wii. The remote control for the Wii gaming console (the "Wiimote") contains a 3-axis accelerometer that is used as the primary input for many of its motion-based games. The Wiimote also contains an infrared camera which tracks the location of two infrared beacons that the user is told to place on top of their television set. The camera, however, is primarily used for pointing applications. Thus, controlling Wiimote accelerations is sufficient for playing most of the motion-based games.

In order to have CRAMER generate the desired accelerations at the Wiimote's accelerometer, we derived the equation that relates wrist angle trajectories to measured linear acceleration. The accelerometer equation is

$$a_m(\theta(t)) = R_a^{\mathsf{T}}(\theta)\left(\dot{J}_a(\theta,\dot{\theta})\dot{\theta} + J_a(\theta)\ddot{\theta} - g\right) \tag{7}$$

where $a_m \in \Re^3$ is the measured acceleration vector, $\theta \in \Re^3$ is the wrist angle vector, $R_a \in \Re^{3\times 3}$ is the rotation matrix relating the axes of the accelerometer to the inertial frame, $J_a \in \Re^{3\times 3}$ is the Jacobian matrix from the wrist to accelerometer, and $g \in \Re^3$ is the gravity vector in the inertial frame. The accelerometer Jacobian satisfies the following relation between wrist angular velocities and accelerometer linear velocities, $\dot{x}_a \in \Re^3$, in an inertial frame:

$$\dot{x}_a = J_a(\theta)\dot{\theta} . \tag{8}$$

Ideally, the problem of finding desired motions to produce a set of desired accelerations could be solved simply by picking a set of initial conditions for the wrist and integrating (7) to get the wrist angle trajectory. However, CRAMER has a limited workspace, and the motors have limited velocity. Further, the accelerometer Jacobian for CRAMER is never invertible since CRAMER cannot produce three independent linear accelerations at its handle . For these reasons, we could not obtain a solution from integration methods.

To obtain solutions for wrist angle trajectories that would produce the desired accelerations, the problem was therefore set up as a function optimization problem. The objective of the optimization was to find the wrist angle trajectory, $\theta(t)$, that would make the measured acceleration, $a_m(t)$, be as close to the desired, $a_d(t)$, as possible. We defined "as close as possible" in a mathematical sense for our cost function as

$$J_c = \frac{1}{2}\int_0^{t_f} \left\| a_m(t) - a_d(t) \right\|_W^2 dt . \tag{9}$$

where the norm is a weighted Euclidian norm with the positive semi-definite weighting matrix, W. We chose to use a weighted norm because it appeared that for many Wii games some of the axes of the accelerometer were less significant for performance in the game. This fact also relieved the impact of the singular accelerometer Jacobian associated with CRAMER since we only needed to generate accelerations on 2 axes.

We identified three categories of constraints on the optimization. The first category was workspace constraints. Each joint was given the constraint that it had to remain within its range of motion for all time. The range of motion of a human wrist was also taken into consideration in the workspace constraints. We placed fairly conservative limits on the amounts of S/P, F/E, and R/U that could be achieved by the wrist to ensure trajectories would not harm patients.

The second constraint category was the actuator constraints. This category was intended to account for the torque and velocity limits of the servomotors. But because different subjects resist motions of CRAMER differently, we are unable to calculate the torque required by each servo to keep them on the desired trajectory. Without a method for computing a torque constraint violation, we decided to neglect the torque limit constraints. So this category consisted only of the constraints that each servo needed to stay within its velocity limits for all time.

The last constraint category was the initial condition constraints. This was an interesting category because, unlike many function optimizations where an initial position is given, our initial position was part of what was to be optimized since accelerations are all that matter. The initial position only had to reside in the workspace of CRAMER and human wrist range of motion, which was covered by the first constraint category. We did however state that the trajectory had to start from rest. So at t=0, the velocity and acceleration were required to be zero.

In order to solve the optimization, we decided to parameterize trajectories and approximate the solution to (9) in discrete time rather than in continuous time. Trajectories for each joint angle were parameterized using Gaussian radial basis functions and a zero offset. The basis functions, of the form

$$\Phi_i[k] = e^{-\left(\frac{(t_i - t[k])}{\sigma}\right)^2} , \tag{10}$$

were given a fixed width using σ, and were centered at t_i. Here, k is the discrete sample number. The angular trajectory of the j^{th} angle in the wrist was computed as

$$\theta_j[k] = h_{j0} + \sum_{i=1}^{N} h_{ji}\Phi_i[k], \tag{11}$$

where h_{j0} is the level of the zero offset and h_{ji} is the height of the i^{th} basis function for that angle. The centers of the N basis functions were spaced evenly over the time interval.

To switch from continuous time to discrete time, we changed the integral of the cost function into a summation and calculated accelerations for specific sample times. Since the accelerometer output of the Wiimote was sampled at 100 Hz, we choose to use 10 ms as our sample time. The workspace and actuator constraints were relaxed from having to remain within their limits for all time, to within their limits at each sample time. This constraint formulation, however, left us with having the total number of constraints of the optimization problem based on the duration of the motion we wanted to reproduce (with about 3000 constraints for a motion with 1 s duration). While this could have been simplified to the maximum and minimum values of the constraints over the time span needed to be within limits, we choose the former because for that case the gradients of the constraints are simpler to calculate.

Accelerations measured by the Wiimote can be obtained by pairing it with a computer using a wireless Bluetooth adapter. Using a managed API called WiimoteLib [21], we made a Visual Basic program to record accelerations from demonstrated motions. We used accelerations recorded from demonstrations by an experienced player as our desired accelerations for evaluating the cost function of the optimization. Solutions to the discrete time, parameterized optimization problem were found using MATLAB's `fmincon` routine.

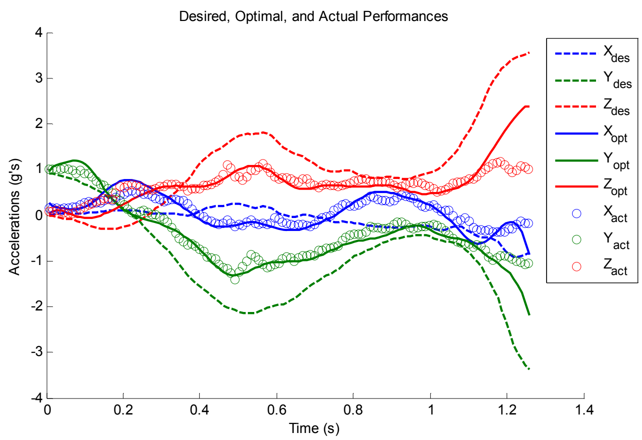

Fig. 6. Accelerations for Bowling measured in g's. The figure shows the original accelerations recorded from a experienced Wii bowler that CRAMER was trying to match, the accelerations that the optimal trajectory of a wrist in CRAMER should achieve, and actual accelerations measured when using CRAMER. The optimal trajectory preserves several features of the desired accelerations, but the magnitude of the accelerations is limited. The actual performance of CRAMER acting on a relaxed wrist shows that throughout the majority of the trajectory the robot closely reproduced the optimal accelerations.

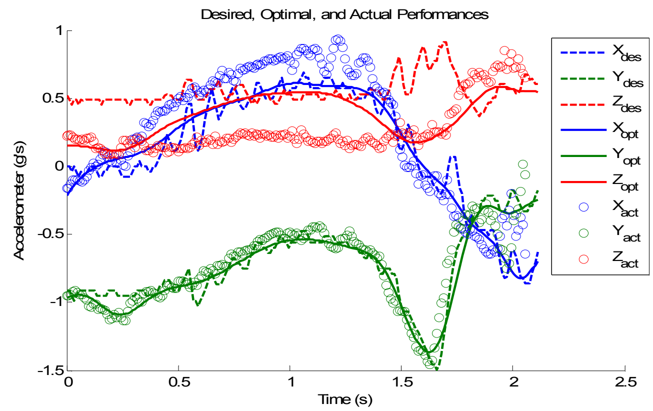

Fig. 5. Accelerations for Golf measured in g's. This figure shows the original accelerations measured from an experienced player putting with their full arm, the accelerations that the optimal trajectory of a wrist in CRAMER should achieve, and actual accelerations measured when using CRAMER. Here, the optimization showed that the accelerations of the optimal trajectory in 2 axes of the accelerometer should closely match the desired values. The actual values from CRAMER acting on a relaxed wrist were also close to the desired.

Two motions of particular interest were the arm motions used to play the sports of bowling or golf. These motions were chosen because the retail package of the Wii console comes bundled with a game called Wii Sports, and the two sports we chose are the only ones in that game that do not involve moving targets. An initial test with CRAMER suggested that the robot would be unable to match the accelerations of full golf swings due to motor saturation, so golf was limited to putting.

After recording accelerations from an average bowl by the experienced player, we used the optimization solver to find a feasible wrist motion that would produce accelerations similar enough to the original that they could still be used to bowl in Wii Sports. Fig. 5 summarizes the acceleration results of the bowling trajectory optimization. When CRAMER was used to move one relaxed subject's wrist through the optimal trajectory, CRAMER was able to bowl easily in Wii Sports.

In the initial testing of golf, the accelerometer measurements of several different strength putts made by an experienced player were recorded in an attempt to accommodate various distances from the hole and different green topographies. We found, however, that CRAMER was incapable of producing accelerations large enough to reproduce putts traveling more than 8 virtual feet on level ground in the game. The lack of putting power of the robot was largely due to the limited speed of the motors. Fig. 6 summarizes the acceleration results for an 8 ft putt. CRAMER was able to putt accurately in Wii Sports with this trajectory and a relaxed subject's wrist in the device.

V. Conclusion

This paper describes a novel device and a motion planning framework for robotic therapy of the forearm and wrist. CRAMER is a low-cost robot for full 3 DOF forearm and wrist rehabilitation. CRAMER's use of a parallel mechanism allows achievement of the desired forearm and wrist motions with only a few, lightweight, low-cost parts. We built the first prototype of CRAMER with hobby servomotors to keep cost down, but the same mechanism design could also be used with other types of motors to improve force control and expand force and velocity range. We note however that we have successfully implemented rudimentary force feedback with the hobby servomotors using strain gauges, which should allow a range of assistive control strategies to be implemented with the hobby servomotor-version of CRAMER.

This paper also presented a trajectory optimization framework for finding motions that a rehabilitation robot such as CRAMER can use to assist people in playing acceleration-based games, such as those for the Wii. A key insight here is that because Wii games are based on only one or two axes of acceleration depending on the game, a wide variety of different human movements and joints can be used to play them. For example, an infinity of different initial configurations of the limb can be used while still generating movements with appropriate accelerations. Likewise, the wrist/forearm can be used (versus the whole arm as is normal for Wii play), as long as the wrist/forearm motion produces an appropriate linear acceleration signal.

We developed a trajectory optimization framework that finds good motions from the many possible. The optimal trajectory, however, may not be intuitive, as was the case for the results from our test with bowling. The motions are suited to the constraints of the specific robot being used to implement the motions, which in our case was CRAMER, and the constraints of the human joints being exercised. The technique generated motions that allowed CRAMER to successfully play Wii bowling and golf putting with a relaxed hand in the device. We note that this trajectory optimization framework could also be used for other robots interacting with other acceleration based-games. While it should be possible to electronically alter the accelerometer signals sent from the Wiimote to achieve desired performance from the games, we choose to try a trajectory optimization method first in order to avoid tampering with Wii hardware or software.

We have not begun clinical testing of CRAMER with the Wii because of two interface problems. First, the Wii games require players to push buttons on the Wiimote during game motions, and most stroke subjects do not have enough finger movement ability to push the buttons. Determining how to emulate a Wiimote would allow us to substitute a different physical input signal for the button push (i.e. one which the patient can achieve) solving this problem.

The second interface problem is that most Wii games require different motions depending on the ongoing, real-time game action, and there is currently no way to communicate the ongoing game action to CRAMER. A means to externally access Wii game status in real-time would solve this problem, allowing CRAMER to help the patient make the movement appropriate for the current game situation.

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