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Closed-chain motion with large mechanical advantage

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Abstract

One of the constraints that severely limit the capability of highly redundant manipulator arms is the actuator torque limits. This paper presents a way to achieve large effective forces from weak actuators by exploiting large mechanical advantage that results from systems near singularities. While large mechanical advantages have been applied near singularities in many instances, this method allows the application of this large force over a large distance. It is applied specifically to closed chain mechanisms and demonstrated on the PolyBot modular self-reconfigurable robot.

1 Introduction

Long serial chain robots with many degrees of freedom (DOF), or hyper-redundant robot arms have a variety of applications including inspection robot arms and snake-like locomotion [Hi90, Bu95] for planetary exploration or search and rescue. Some modular, reconfigurable systems that use many repeated modules [Ca00, Yi00] use long serial chains as parts of a larger system as an octopus might. One problem with using serial chains is the limited strength of the actuation [Ni98]. Since the number of modules within a chain is variable, the strength required to maneuver the chain varies, and at some point, there will be more modules than the system's actuators can support. A closed chain is a serial chain with both ends attached. Closed chains can resemble long serial chains by simply flattening the loop.

In typical robot arm control, configurations which correspond to singularities in the Jacobian matrix are typically avoided to prevent excessive joint velocities or torques. Redundant manipulators have sometimes used the extra DOF to enhance this avoidance. This paper proposes not to avoid singularities but rather the opposite, to remain close to them exploiting the near infinite mechanical advantage near singularities[Ki94, Go90].

In biology animals often exploit singularities in this fashion. The easiest example is to look at human walking. After a forward step, the heel makes contact with the ground, the leg straightens as it begins to take on the weight of the body. When the leg is straight the Jacobian matrix describing the relationship between the joints (hip and knee) and the position of the foot becomes singular. Also, the mechanical advantage of the system gets larger - as the knee gets closer and closer to straight, the force that the hamstring muscles can apply parallel to the direction of the leg gets larger. A reason humans may do this is that the effort on the muscles (and thus energy expenditure) is correspondingly reduced by the large mechanical advantage.

This paper presents a method for obtaining large variable mechanical advantage for closed chain serial manipulators with rotational DOF. A key additional requirement is some form of lock or brake to these DOF's. By lock, we mean a method by which the DOF can be made rigid independent of the strength of the actuator. This can be an additional active brake, or self-locking (non-backdriveable) actuator. The method easily extends generally to a large variety of systems, in fact, it can apply to any mechanical system that has all of the following four properties:

- **redundancy** or extra degrees of freedom.
- **locking mechanism** or brake on each DOF,
- **parallelism** (or closed chain) configuration, and
- **singularness** there must be a configuration where the Jacobian is singular.

Section 2 presents the method in detail which theoretically can obtain near infinite forces with near zero actuation. Section 3 addresses the practical considerations to obtain more reasonable results. Finally Section 4 presents several experiments that verify the technique followed by conclusions.

2 Method and Intuition

The idea is to exploit the theoretically near infinite mechanical advantage that can be obtained when a system is near a singularity. By repeatedly switching a subset of the motors to be active and the rest locked, a ratcheting kind of action can be used to move links to positions while under large external forces. If the size of each ratchet motion can be made

Figure 1: A set of 8 PolyBot G1v4 modules, note the top three are colinear.

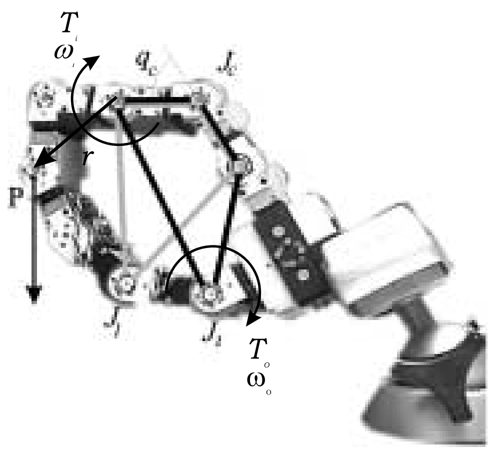

Figure 2: Closed chain showing two alternating fourbar sets, (black and grey) with the other modules locked

arbitrarily small, it can be arbitrarily close to the singularity with arbitrarily large mechanical advantage. Thus, weak motors can be used to provide arbitrarily large forces. Of course there are practical limits to this method.

This technique is especially well suited for modular reconfigurable systems like PolyBot [Yi00] and CONRO [Ca00]. We will use PolyBot to illustrate the method. PolyBot is a modular reconfigurable robot system with two types of modules, a *segment* with one rotational DOF and a *node* with zero DOF. Figure 1 shows a set of 8 PolyBot segment modules configured in a closed chain that moves in the plane with external forces applied to it. The mechanical advantage of different joints varies depending on the geometry of the configuration. The problem can then be posed, given an initial configuration, what set of motions will result in the system reaching a goal configuration while maintaining actuator torque constraints?

By locking all but four of the joints, the system kinematically can be viewed as a fourbar linkage. Figure 2 shows a

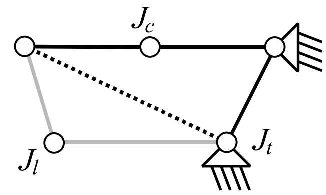

Figure 3: **Step 1** J_c is in singularity; J_t is unlocked, J_l is locked. The triangle formed with the dotted line indicates the fourth bar of a fourbar linkage since J_l is locked.

schematic representation of a fourbar overlayed with black lines on a photo, with an external load applied at P. If we consider an output torque T_o seen at a target joint, J_t, and an input torque $T_i = P \times r$ applied at one of the other three joints, the mechanical advantage M can be expressed by the following equation.

$$M = \frac{T_o}{T_i} = -\frac{\omega_i}{\omega_o} \tag{1}$$

From the principle of virtual work we know that M is the negative reciprocal of the velocity ratio, input velocity ω_i over output velocity ω_o. Further analysis of the geometry shows that the velocity ω_o is proportional to $\sin(q_c)$ and so goes to zero as q_c approaches zero [Shig80].

From Equation 1, it is easy to see M grows very large as J_c in Figure 2, becomes straight ($q_c = 0$) as in Figure 1. When $q_c = 0$ the fourbar is said to be *in toggle*. This configuration is well known to have infinite mechanical advantage and is used in many devices to apply large forces such as clamps or fixturing devices [Shig80]. More generally, the Jacobian of the system is singular. For one DOF systems, the singularness corresponds to mechanical advantage.

In the fourbar case, we treated the system has having a single input and a single output. In our case however there are many joints that can apply forces as input. Since we are concerned with the extreme condition where actuators are at their limit, we can consider all the actuators acting together as a virtual actuator, acting on the single DOF.

While clamps and fixtures have infinite mechanical advantage at the singularity (one point in the configuration space) and very large mechanical advantage in a very small range near the singularity, our problem requires large mechanical advantages over a *large* range of motion.

Motions away from the singularity (e.g. joint, J_c with q_c close to 0 degrees (as in Figure 1), in a fourbar moving away from 0 degrees) will cause a point P, where an external force is applied, to move in one direction, initially with infinite mechanical advantage. We call this a *weakening* move as the mechanical advantage starts high and becomes lower. Conversely, motions toward the singularity will cause P to

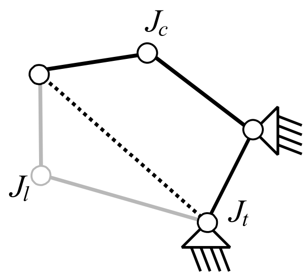

Figure 4: **Step 2** Weakening move J_c away from singularity. J_l is still locked. J_t moves down.

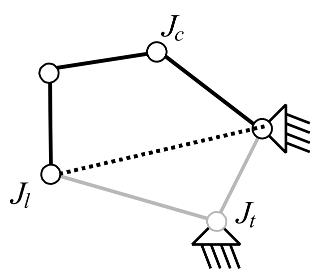

Figure 5: **Step 3** Lock J_t and unlock J_l. A new virtual four-bar linkage is now apparent shown by the new dotted line.

move in the other direction with increasing mechanical advantage up to infinity as the singularity is reached. Correspondingly we call this a *strengthening* move.

2.1 Algorithm

With these two motions, weakening and strengthening moves, and alternating which sets of joints are locked, a target joint, J_t can theoretically be moved to any position with arbitrarily large mechanical advantage and arbitrarily weak motors, if J_c starts near a singularity.

The steps required to move J_t to an arbitrary position are illustrated in Figures 3- 5 and are described below:

1. J_c is in singularity; unlock J_t, lock J_l, see Figure 3.

2. Weakening move J_c away from singularity, see Figure 4. Here J_t makes forward progress.

3. Lock J_t and unlock J_l, see Figure 5.

4. Strengthening move J_c back to singularity, see Figure 6. Here the system is resetting, no progress is made, but none is lost either.

5. If J_t has reached the target position then stop, otherwise repeat from step 1.

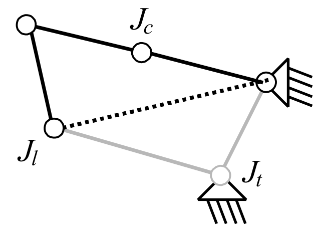

Figure 6: **Step 4** Strengthening move J_c back to singularity while J_t does not move since it's locked.

The resulting motion has a ratcheting effect; each time J_t is locked, it has ratcheted up some small forward progress. At any time, only one of J_l or J_t is locked. It is interesting to note that reversing the parity of which of the two is locked during the weakening step reverses the direction of progress.

To move a system from one configuration to another, this process of moving one target joint J_t to its goal configuration can be repeated for most of the joints in the system, permanently locking each joint as it reaches its goal. One joint (e.g. J_c) can be used as the joint to move in and out of singularity for all of the other joints. This process can be applied to all joints except the last set of four (one DOF four-bar) which would require a motion without advantage.

2.2 Motions without advantage

With the weakening move, the system starts with infinite mechanical advantage, so we know that the joint can make some non-zero forward progress. A problem is that after a weakening move, the strengthening move may not have a large enough mechanical advantage to start with.

If we can calculate beforehand, how much force is required to move P for a strengthening move, we just need to be sure that J_c never moves far enough from the singular position during the weakening move to lose enough mechanical advantage for the next strengthening move.

Alternatively, the system can search for the appropriate positioning. If a strengthening move fails, the system can backtrack, losing some of the forward progress, but moving J_c closer to the singularity. This can be repeated until the strengthening move succeeds.

Initial and Final Conditions In a larger context, moving a system from one arbitrary configuration to another with all the joint angles specified may use this method as a component. We have assumed so far that the system starts with a joint, J_c in a singularity, but generally speaking this will not be the case. If it does not start in a singularity the system must be brought into a singularity without using the high mechanical advantage. The end condition is a dual.

There are three cases for which solutions are easy.

- The actuators may be initially strong enough to move to a singular configuration.
- Links may be under external forces which push the system towards towards a singularity.
- The system may already be in a singularity (by design or otherwise).

For the planning problem, almost any choice of different joints is a potential solution, so long as the initial and final conditions can be met (that is getting close to a singularity to start with, and moving out of the singularity towards the final goal position to end). The choice of the sequence of joint sets J_c, J_l and J_t can often be chosen such that one of the three cases above holds for both the initial and final move.

There are many possible sets of joints J_c, J_t and J_l, depending on how many joints are in the system. For example, with 8 modules in one configuration there are $(n(n-1)(n-2)) = 336$ possible joint sets. It is likely that at least one will be one of the three cases above, although this is not guaranteed.

3 Practical considerations

In practical terms, this method cannot be used to apply near infinite forces with near zero strength actuators. There are several factors that affect the maximum useful mechanical advantage, including: discrete locking positions, imprecise sensing, non-rigid links, imprecise joints, brake/ratchet strength limit, internal forces, friction and inertia.

Many of the above limitations result in the same type of failure. In order for the system to work, forward progress must be made with each cycle of the 4 steps. One of the above limitations may cause the system to either make no progress at every cycle or to backslide at arbitrary points.

For example, discrete locking positions, like with a ratcheting saw-tooth gear system, require that during the weakening move, the target joint must move past one gear tooth. Otherwise, the ratchet will not make incremental progress but will slide back and lock at the original position. Non-rigid links and imprecise joints also cause a similar action at the ratchet or brake. In this case, the rest of the system may be moving forward but the target joint does not see any motion because of link flexing or joint slop. So again, the target joint does not make progress. Internal forces and friction or other forces which cause hysteresis can have a similar effect.

If sensors which measure the joint positions are inaccurate, then the system may not be moved precisely to the singularity. The larger the position error, the further from the singularity the system will be during the weakening move and consequently, the lower the theoretical maximum mechanical advantage.

Other forms of failure include the brake or ratchet strength limit. Clearly, if torques are applied greater than the brake or ratchet can support, the system will fail. Typically, these systems can withstand an order of magnitude or more torque than the actuators limits in a modular system.

Another assumption we have made is that the links themselves have no mass, and thus either gravity or dynamic motion require no forces. In real systems the actuators must have torque enough to overcome these forces and other internal forces and torques before they can apply any forces to external loads.

On the other hand while it has been implied that static forces and motions are used, the dynamics of a system may aid in making progress. For example, vibrating at a resonant frequency is one way to achieve larger motions with smaller incremental forces. This can be used especially effectively with a ratcheting type locking mechanism.

Applications to other systems This method may be applied to loop configurations of the CONRO system if the CONRO modules were modified to incorporate a brake. The Dragon system proposed by Nilsson [Ni98] is a modular system that has brakes built in and if configured in a loop could also use this method.

We can actually apply this method to any system that has the four components listed in the introduction, redundancy, locking mechanism, parallelism and singularness. Even systems that are not modular robots.

In order to ratchet, essentially, the system must be able to emulate two different one DOF structural linkage mechanisms; one for the progress phase and one for the reset phase. Having two different locking states effectively emulates two different linkage mechanisms. Redundancy allows the locking of joints without the loss of functionality. Parallelism is needed in order for the system to support external forces without collapsing during the reset phase. Lastly, this method exploits near infinite mechanical advantage M, and so there needs to be configurations in the system with near infinite M for the method to work. This last property is not guaranteed to exist for any arbitrary system, however singularities in the Jacobian (that are not a function of the representation e.g. Euler angle representation of orientations) should result in near infinite M.

This method should also work for systems that have prismatic as well as revolute joints that have the four properties above. A system that has only prismatic joints (like two gantries attached at the end effector) will not have any configurations with near infinite M (the reader is left to verify this). Other systems that are candidates are redundant parallel mechanisms similar to stewart platforms.

4 Experimental Verification

Figure 7: One PolyBot G1v4 module with computer, batteries and one DOF.

The physical system in Figures 1 and 2 are made up of eight G1v4 modules (shown in Figure 7 which are made up of a hobby RC servo, onboard computer and batteries with an added external brake on each module. The brake locks the structure (two frames together) by applying friction on a disk. In Figure 2 the servo with the double circle overlay was the only actuator activated, the other actuators were backdriven by this servo.

The method worked for fairly small loads, less than 100 gm attached at P; the target joint J_t was able to move close to 90 degrees while lifting the load. It was not able to move at all if the brakes were released. Larger loads caused the system to fail.

As a load was increased at point P in Figure 2, the compliance in the system caused the method to fail. During the weakening move, J_t would make progress, then it would be locked for the following strengthening move. When the first step is repeated, as J_t is unlocked, J_t would sag back down removing the progress achieved earlier. This sag is due to the compliance in the joints.

To improve this, a system using a “roller ratchet” was tested. A roller ratchet is a ratcheting mechanism without teeth, having very little backlash that allows a joint to move in only one direction as shown in Figure 9.

Rollers are arranged around a lobed cylinder. These rollers are positioned by moving the positioning frame to engage for clockwise or counter clockwise motion. In the plan

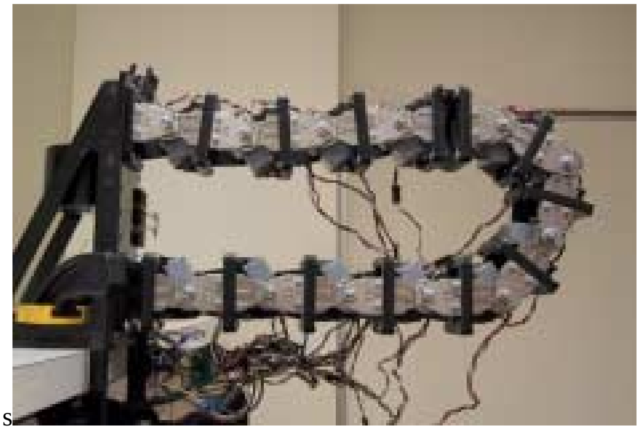

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Figure 8: Roller ratchet equipped closed chain with 12 modules.

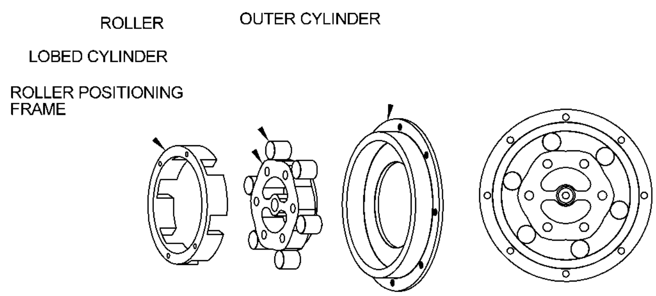

Figure 9: Roller ratchet schematic.

view Figure, the rollers are positioned such that the outer frame can be moved clockwise relative to the lobed inner cylinder, but the rollers become jammed for counterclockwise motion.

Thus the system does not need a step to unlock J_t or J_l, the ratchet will effectively do so whenever the joint will move in the desired direction and will lock otherwise. A prototype roller ratchet system with 12 modules (see Figure 8) succeeded in lifting 5 N applied at the distal end equivalent to approximately 0.1 N m of torque. Without the ratcheting system, the modules could just lift its own weight of 2300 gms. The system was limited by failure of the ratcheting mechanism in the form of slip and deformation of the material.

5 Conclusions

By exploiting the mechanical advantage near singularities, forces beyond the normal abilities of the actuators can be applied to external loads. This promises to be a key enabler for modular robots with increasing numbers of modules attached in chains. A new roller ratchet system currently being designed that should result an increase of 10 times in the output torque of the system which will be implemented in the third generation (G3) of PolyBot. Other future work includes finding guaranteed methods for planning the motions, and formalizations for non-planar systems.

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References

[Bu95] Burdick, J.W., Radfor, J., Chirikjian, G.S., “A ’sidewinding’ locomotion gait for hyper-redundant robots” in *Advanced Robotics* 1995. vol.9, no.3, p. 195-216

[Ca00] Castano, A., Shen W.M. and Will, P., “CONRO: towards deployable robots with inter-robot metamorphic capabilities,” in *Autonomous Robots* Kluwer Academic Publishers, June 2000. vol.8, no.3, p. 309-24

[Do99] Dowling, K. “Limbless locomotion: learning to crawl” in *Proc. of IEEE Intl. Conf. on Robotics & Automation* Detroit MI, May 1999 vol 4. p. 3001-6

[Go90] Gosselin, C. and Angeles, J., “Singularity analysis of closed-loop kinematic chains,” in *IEEE Transactions on Robotics & Automation* June 1990. vol.6, no.3, p. 281-90

[Hi90] Hirose, S. and Morishima, A., “Design and control of a mobile robot with an articulated body” in *Intl. J. of Robotics Research* April 1990. vol.9, no.2, p. 99-114

[Ki94] Kieffer, J., Lenarcic, J. “On the exploitation of mechanical advantage near robot singularities,” in *Informatica* Oct. 1994. vol.18, no.3, p. 315-23

[Ni98] Nilsson, M. et al. “Snake robot-free climbing” in *IEEE Control Systems Magazine*, Feb. 1998. vol.18, no.1, p. 21-6.

[Pa95] Paljug, E., Ohm, T. and Hayate, S., “The JPL Serpentine Robot: a 12-DOF system for inspection” in *Proc. of 1995 IEEE Intl. Conf. on Robotics & Automation* Nagoya, Japan, May 1995. vol.3 p. 3143-8

[Shig80] Shigley, J.E and Uicker, J.J. Jr. *Theory of Machines and Mechanisms* McGraw-Hill Inc., 1980. p. 109-12

[Yi00] Yim, M. et al., “PolyBot: A Modular Reconfigurable Robot,” in *Proc. of the 2000 IEEE Intl. Conf. on Robotics & Automation*, May 2000. vol.1 p. 514-20