Chapter 7

Examples

This chapter describes a number of example applications using oscillators which further demonstrate their versatility. The tasks differ from the ones described in previous chapters by consisting of a single motion, rather than continuous motions. The oscillator dynamics are used to produce these motions, with feedback being used to modify the oscillator outputs in the usual way.

The first half of the chapter describes using the oscillators for a task which is partly rhythmic and partly discrete: the task of drumming. The "beat" is a continuous signal, while the individual drum beats are discrete. The oscillator system uses auditory feedback of the sound of the drumming to create and maintain a steady beating rhythm. The chapter shows how the oscillator properties make it easy to beat in time with another drummer, and construct a variety of different rhythms, using both one and two arms.

The second half of the chapter describes the tasks of throwing, hitting and hammering. The oscillators are used to drive the arm back and forward in a single motion to achieve a good throw or a powerful hit. These motions exploit the natural dynamics by storing and releasing energy in the joints of the arm, and also exploit the oscillator properties, the oscillators responding to the system dynamics. The effect of feedback in these discrete tasks is less clear than in the continuous case, although it appears to have approximately the correct effect: making the arm move faster.

7.1 Drumming

The first example in this chapter is drumming. This task combines elements of the rhythmic motions described in previous chapters with discrete motions. The overall rhythm or beat is a continuous signal, while the individual hits on the drum are discrete. The example also shows how other sensory modalities can be used as feedback to the oscillators. In this case auditory feedback (the sound of the drum) is used to modify the oscillator behavior. This has interesting and useful properties as described in this section.

The overall setup is illustrated in figure 7-1, and a picture of the robot drumming is included in figure 7-2. An oscillator is used to drive either the wrist or the elbow of the robot to hit the drum. The master-slave oscillator system described in section 5.3 was also used to drive the elbow and wrist joints as a single unit. The sound of the drumming was recorded by a microphone, processed and applied as an input to the oscillators. The auditory processing is simple, with the raw auditory signal sampled at 8kHz, and thresholded to find the sound of the drum. This is then low-pass filtered and subsampled to reduce the sampling rate to around 50Hz, an appropriate rate for the oscillators.

The drumming action of the robot is accomplished by moving the arm up and down, with the drum being hit on the down stroke. When the arm is still, the drum stick is held slightly above the drum, so it actually hits the drum on the follow through. This is similar to the hitting and throwing examples in the previous sections. Human drummers grip the drumstick lightly and exploit the dynamics of the stick on the drum to achieve high frequency rolls. The light grip has the added advantage of reducing the inertia of the stick so it can bounce on the drum and make a good note. To achieve this on the robot, a simple passive hand was built to hold the drumstick, as shown in

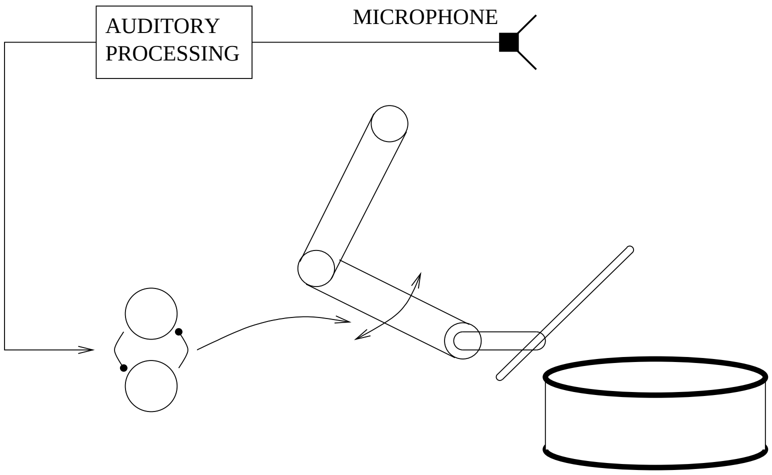

Figure 7-1: Schematic of drumming. The system is set up so that the drumming task is a auditory-motor loop, where the action of the oscillators is to drive the arm to hit the drum, and the sound of the drum is recorded and used as an input to the oscillator. Details of the auditory processing are included in the text.

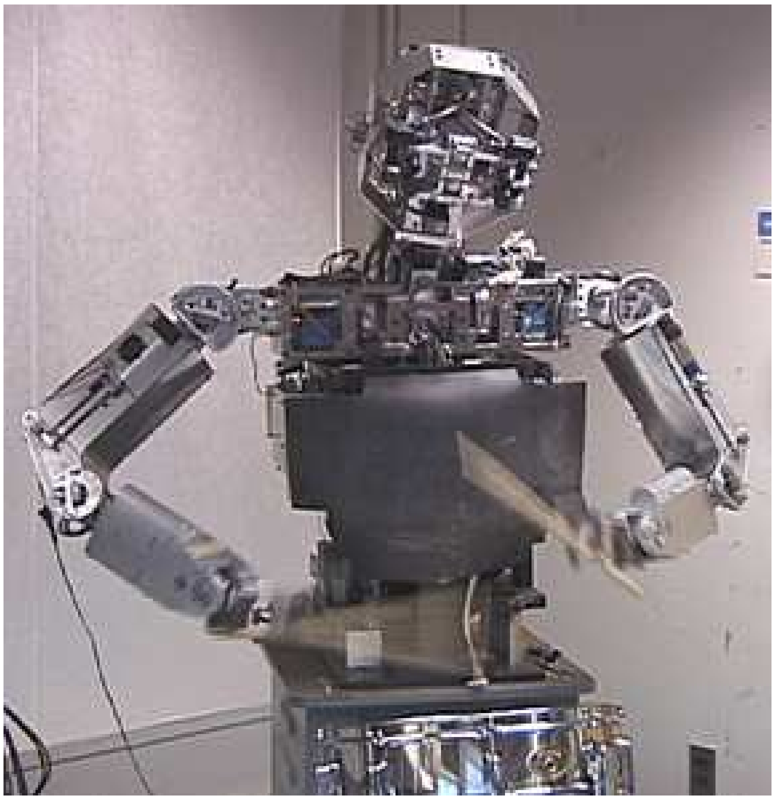

Figure 7-2: Picture of Cog hitting a drum. The robot uses its elbow and wrist joints to move the arm up and down, so hitting the drum.

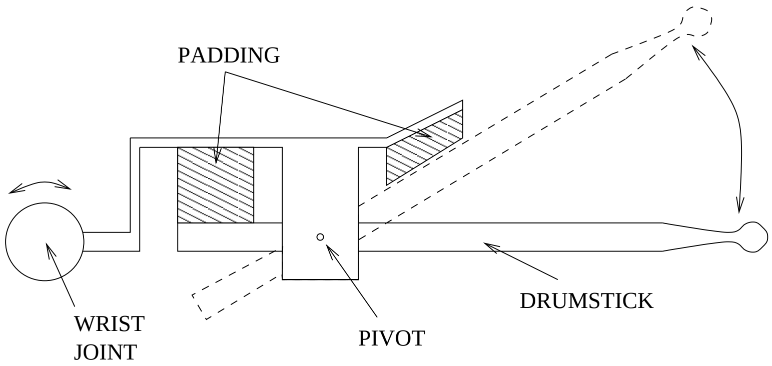

Figure 7-3: Drumstick holder. This special purpose hand was made for the robot to hold the drumstick. The stick swings freely on a pivot, rotating between two pads made of either rubber or felt. The whole hand is rotated by the wrist joint of the robot. When the hand is moved up and down, the stick swings on the pivot, and bounces on the drum. The interaction of the drum, stick and pads can be used to get single or multiple hits on the drum, exploiting the bounce of the drum head.

figure 7-3. The stick is pivoted so it can swing freely, its motion damped by two felt or rubber pads. By using a piece of tape to modulate the free motion of the stick, the number of bounces of the stick on the drum could be controlled. This passive system worked well. Other researchers have considered active low impedance holders for drumsticks with similar results (Hajian et al., 1997).

The overall system (shown in figure 7-1) forms a closed auditory-motor loop. There are considerable delays in the system, mostly in transferring the auditory signals to the oscillators, and from the command to move the arm to the actual hit on the drum.[1] These delays combine with the oscillator dynamics to create a limit cycle drumming solution with a steady beat, as shown in figure 7-4. The main effect of the feedback is to make the drumming faster, and because the stick is moving faster the sound is slightly louder. The auditory signal is a series of spikes, but is strong enough to cause entrainment of the oscillators.

By entraining the oscillators to the sound of drumming, the oscillator system produces a steady beat without requiring a timer. This is important for the particular implementation of the robot arm, because there is no global clock. The system does not require any model of the delays in the system, and in fact requires the delays in order to work. The tuning of the system is also simple, because of the robustness to the value of the input gain (see chapter 3). As long as the gain is large enough to cause entrainment, its exact value is not important.

Since the oscillators use the raw auditory signal as an input it can respond to other noises, such as an additional drum beat. The oscillator adjusts its phase and frequency to beat in phase with the extra beat. This effect is shown in figure 7-5. One arm of the robot was used to produce a constant beat, and the other arm was controlled with an oscillator. The effect of the feedback is make the oscillator driven arm hit in phase with the extra beat.

Hitting in phase is the only possible solution because the robot "hears" both beats. The stable limit cycle without the extra noise has the arm hitting just before the noise, so the stable entrained cycle with the extra beat must have the same characteristic. Thus the only stable cycle is one where the oscillator hits in phase with the extra beat. Because the speed of the limit cycle is determined by the delays in the system, the range of frequencies with exact synchronization is quite small (in the range 9.3 to 10.3 rad/s about a "natural" frequency of 9.8 rad/s). If the oscillator only responds to the extra beat and ignores the sound that it makes then it can entrain over a wider range of frequencies, although the hits are not exactly in phase. Changing time constants and delays in the

[1]The architecture for the system is described in Appendix A.

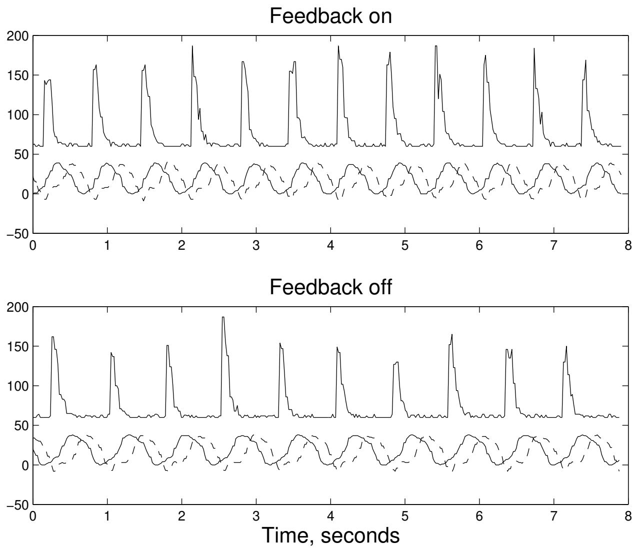

Figure 7-4: $\boxed{\text{REAL}}$ Plot showing the effect of feedback on the drumming system. The plots show the auditory signal (top trace in both plots), the command to the joints (solid line) and the actual joint motion (dashed). The drum is hit when the arm is moving down. The main effect of the feedback is to speed up the drumming, which has the consequence of making more noise. The final speed of the drumming is determined by the delays in the system, which are dominated here by the delay from the command to the arm to the arm actually moving. The shape of the auditory signal is quite different from a sine wave, yet the oscillators can still entrain to it.

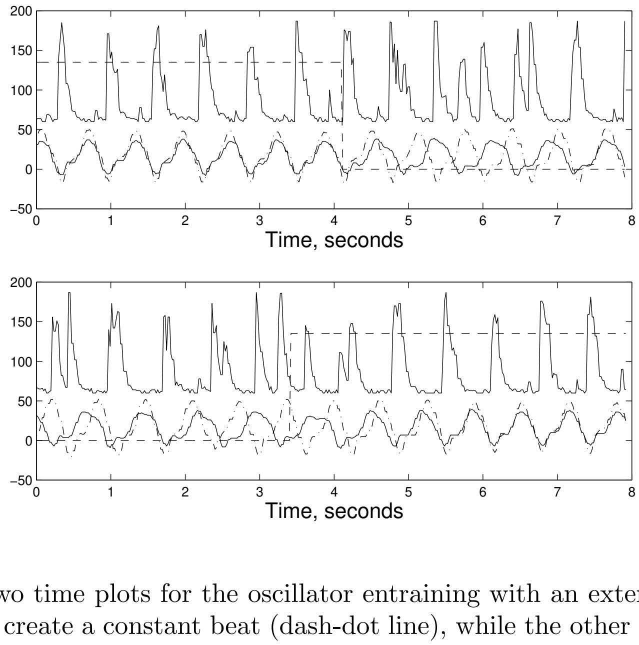

Figure 7-5: $\boxed{\text{REAL}}$ Two time plots for the oscillator entraining with an external beat. One arm of the robot was used to create a constant beat (dash-dot line), while the other arm used the auditory signal (top trace) to control the arm motion (solid line). The feedback gain is indicated by the dashed line. When the feedback is on, the oscillator drives the arm in phase with the external beat, and when it is off there is no coordination.

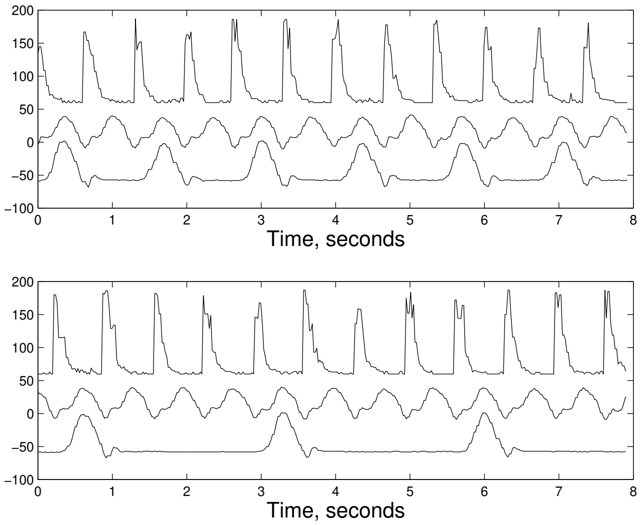

Figure 7-6: $\boxed{\text{REAL}}$ Plot showing examples of different rhythms possible using counting. The top plot shows the auditory signal (top trace), the motion of the dominant arm (middle trace), and the motion of the second arm which is hitting every second beat. The lower plot shows the same, but the second arm is hitting every fourth beat. Since the underlying oscillator for the second arm is entrained to the auditory signal, the two arms hit in phase. The up and down motion of the arm is visible in the lower traces, the drum being hit on the follow through, after the arm has been lifted up and down.

system, either by introducing new delays, or changing the stiffness of the arm can change the limit cycle frequency.

This example illustrates the power of coupling systems using feedback from the environment. It is only because the sound of the two drums is combined by being detected with a single microphone that the oscillator beats in phase.

7.1.1 Counting

This section describes how the drumming can be extended to using two arms, and how the auditory-motor loop can be used to synchronize the arms with one another, even when the arms are beating at different rates.

Synchronizing two arms using the oscillators is easy, by using an oscillator for each arm and feeding both oscillators the same auditory signal. Since the coordination of the system is determined by how the oscillators entrain with the auditory signal, both arms will make the same motion, and so hit the drum in phase. The architecture of the system (see Appendix A) has the controllers for each arm in separate processors, with low bandwidth communication between the processors. Applying the feedback separately allows both arms to be coordinated with one another using a distributed control system.

Getting the arms to hit at different rates can be achieved by using something analogous to counting. Say for example one arm is hitting every cycle, and we want the other arm to hit on every other cycle. A simple way to achieve this is to keep the oscillator for the second arm synchronized to the auditory signal (so oscillating in phase with the first arm), but only use its output to drive the arm every other cycle. The counting is easily implemented by counting the cycles of the oscillator

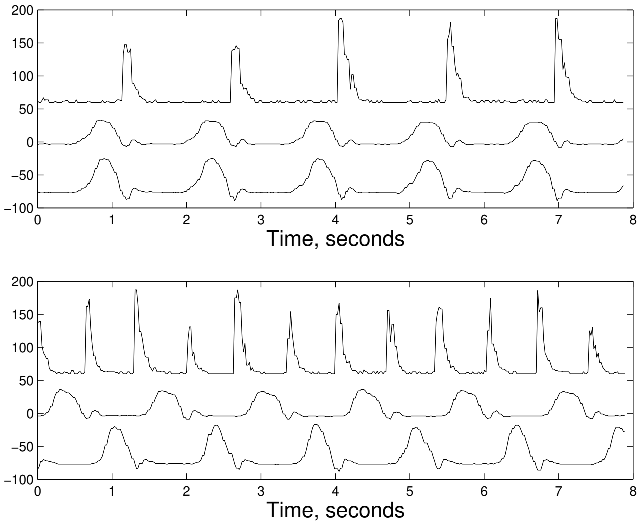

Figure 7-7: $\boxed{\text{REAL}}$ Plot showing two stable limit cycles when the arms both hit on every other beat. The top graph shows the slow cycle, the arms hitting together, and the lower graph shows the arm hitting alternately. The speed of the faster cycle is the same as if it were made by one arm drumming on every beat.

since the last hit. The robotic performance of this rhythm is shown in figure 7-6.

An interesting limit cycle is created when both arms hit on alternate cycles. This results in two auditory-motor limit cycles, one slow cycle where the arms beat in phase, and one faster one where the arms beat alternately. These are shown in figure 7-7. Both cycles appear to be stable, and can be switched from one to another by disturbing the system with an extra auditory signal as shown in figure 7-8. The oscillators for the two arms are completely independent, but are coordinated with one another using the common auditory signal.

7.1.2 Hitting on the offbeat

Another extension of the system allows the arms to hit between the beats. This is easily achieved by inverting the sign of the feedback signal to one of the arms. This will cause that arm's oscillator to entrain out of phase with the other arm, and so hit the drum halfway between the other arm's beats. Unfortunately, hitting in this way creates a more complex auditory signal, to which the oscillators cannot easily entrain. The system needs to ignore the extra beats, and only pay attention to the dominant beat.

One solution to this problem is to improve the auditory processing to ignore the extra beat. There is a considerable literature on beat tracking (e.g. Scheirer (1998)), and the task here is simplified by the clean sound of the drum.

An alternative and simpler solution is to inhibit the auditory feedback except when a sound is expected, i.e. only listen for a short period after the motion of the dominant arm. This was implemented on the arm, and was successful at producing a range of rhythms, with the entrainment of the system undisturbed by the offbeats. Rhythms hitting every fourth, second and alternate beats are shown in figure 7-9. It is also easy to change the rhythm produced by the arms, by altering the number of beats "counted", as shown in figure 7-10. Since the system only listens for a short period after the motion of the dominant arm, changing the second arm does not disturb the steady

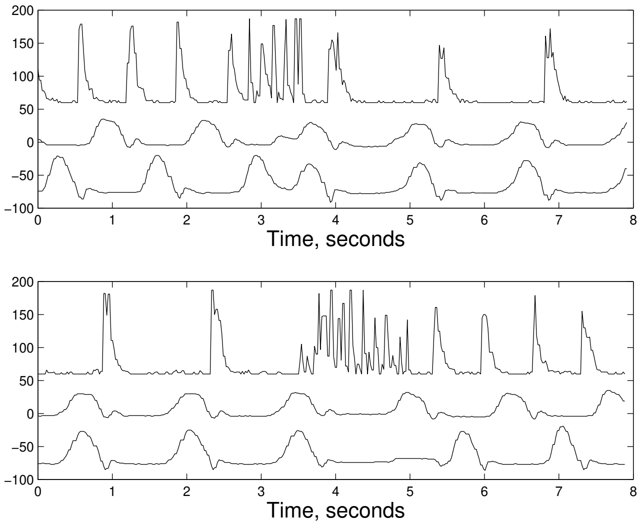

Figure 7-8: $\boxed{\text{REAL}}$ Plot showing how an auditory disturbance can alter the limit cycle found by the oscillator when each arm hits on alternate beats. The disturbance was from a third drumstick banging the drum, which caused the system to switch from fast to slow (top graph) or slow to fast (lower graph).

entrained beating pattern.

7.1.3 Hitting more than one drum

It is also possible to use an extra oscillator to enable the system to hit more than one drum. As described in chapter 3, the setpoint for the whole arm is generated by adding the normal oscillator output y_{out} to a fixed posture θ_p:

$$\theta_v = \theta_p + y_{out} \tag{7.1}$$

The posture does not need to be fixed, and can be generated by the output of another oscillator. If that oscillator provides a series of steps, then the arm will move backwards and forwards between two locations. If this movement is superimposed on the drumming, the arm will hit two different drums. The synchronization between the drumming and the posture change is obtained by using the auditory signal to entrain the posture oscillator.

This method was used to hit a drum and a cymbal as shown in figure 7-11. Unfortunately, the auditory feedback was not clean enough in this case to get the oscillators to entrain. A fake sine wave signal was used instead, which was easier to entrain with.

The oscillator system was used for a variety of percussion instruments, including tambourines, maracas, cow bells etc. For some of these (e.g. the maracas), the auditory signal was sufficiently complex for the simple auditory processing to not be able to extract a signal which the oscillators could entrain with. In those cases a sine wave was used to produce the rhythms.

7.2 Discrete from rhythmic

The discrete motions which are considered in the rest of this chapter are single, dynamic motions which contrast with the continuous dynamic tasks in the previous chapters. For example, a golf

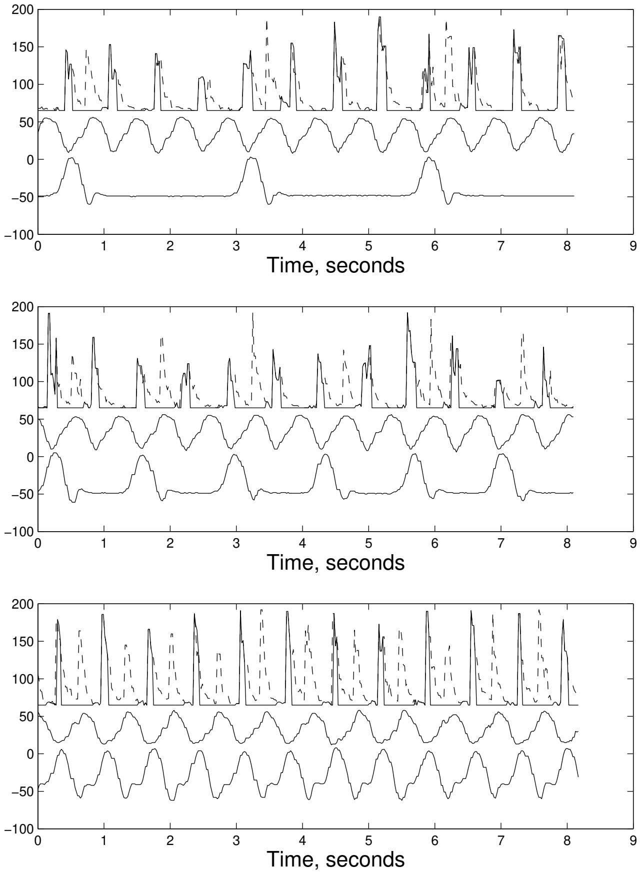

Figure 7-9: $\boxed{\text{REAL}}$ Three different rhythms which use the motion of the dominant arm to inhibit the auditory processing. The plots show the raw auditory signal (dashed), together with the signal applied to the oscillators (top solid trace), and the two arm motions. Since the oscillator only "listens" for a short period (approx 0.25s) following the motion of the arm, the sound of the second arm drumming on the offbeat is ignored. This allows the system to remain entrained.

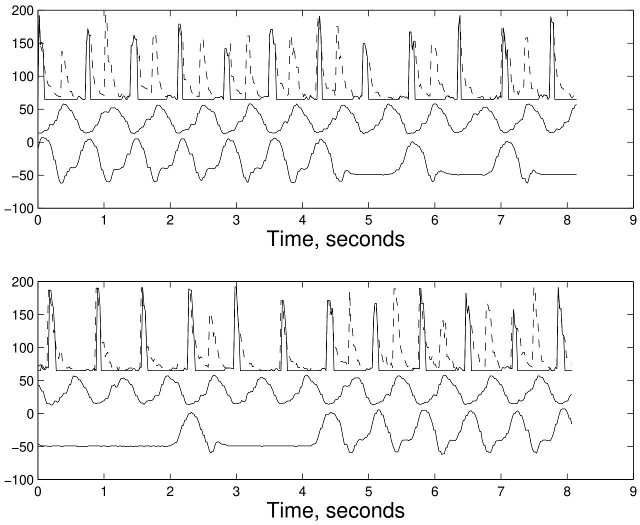

Figure 7-10: REAL Switching between different rhythms. By changing the number of beats which are "counted" by the oscillator, the system can change the rhythm produced. The top plot shows the second arm changing from hitting every other beat, to hitting every second, and the lower plot shows the change from every fourth, to alternate beats. The auditory signals are shown as described in figure 7-9.

swing is a discrete dynamical motion, while the actions during eating are also discrete but less obviously dynamic! The commands required for this kind of motion are pulses and steps, which can be obtained by starting and stopping the oscillator at peaks in its output, as shown in figure 7-12. Pulses are created by stopping at peaks of the same sign, while steps by stopping at peaks of opposite sign.[2]

Feedback can be applied to this discrete oscillator system exactly as in the rhythmic case. The effect of feedback is more complex because the final motion is not a converged limit cycle, but the transient trajectory towards that limit cycle. The oscillator entrains quickly, which implies that the feedback will have an effect. Because the oscillator tends to find resonant-like motions when run continuously, one would expect the transient to have the quality of "moving towards resonant-like motions", or injecting energy into the system. Like the continuous case, the feedback should make the oscillators sensitive to the arm dynamics, and create movement where an appreciable amount of energy is stored and released in the arm springs.

Schöner (1990) also suggested using a rhythmic system to produce discrete motions. His system was perhaps more mathematically elegant than the solution presented here, although it was sensitive to parameter values and not used for any practical purpose.

7.3 Throwing

The throwing task was implemented by using the oscillators in discrete mode to drive the joints of the arm. There was no connection between the joints except through mechanical coupling, and the feedback to the oscillators was from the joint angles of the arm.

Figure 7-13 shows a sequence through an underarm throwing action implemented on the robot.

[2]The peaks can be easily detected by checking the zero crossings of the rate of change of oscillator output $\dot{y}_{out}$.

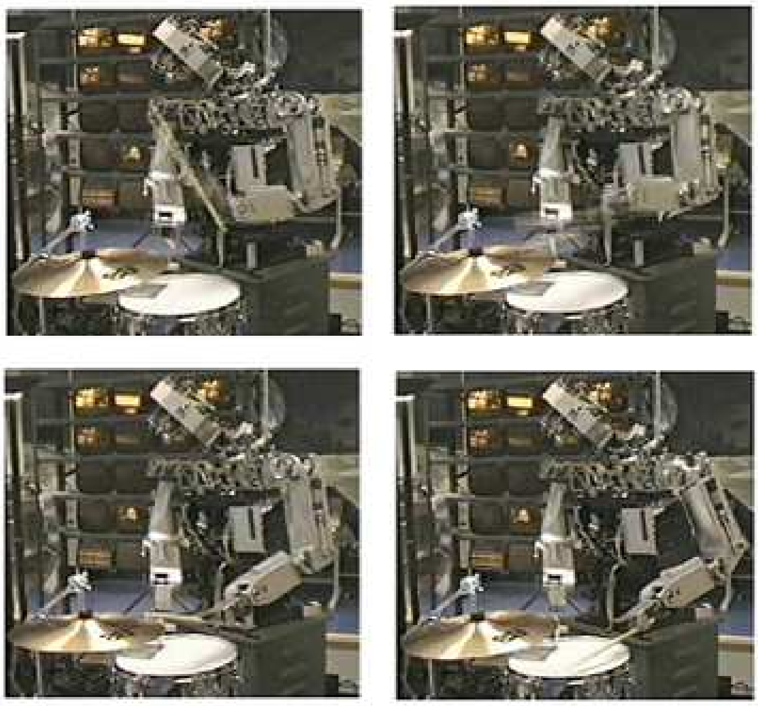

Figure 7-11: $\boxed{\text{REAL}}$ Four stills from a video of the robot drumming. The pictures are in no particular order. The robot uses its right arm to hit the drum, and its left arm alternates between the drum and the cymbal.

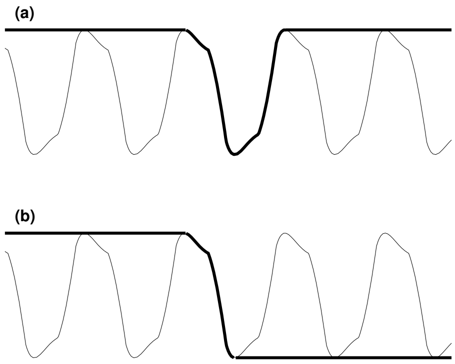

Figure 7-12: Schematic of discrete motion. A single cycle of the oscillator can be used to create single motions by detecting peaks in the oscillator output and stopping and starting the integration. The thin line shows the usual oscillator output, and the thick line shows how this can generate **(a)** a pulse and **(b)** a step.

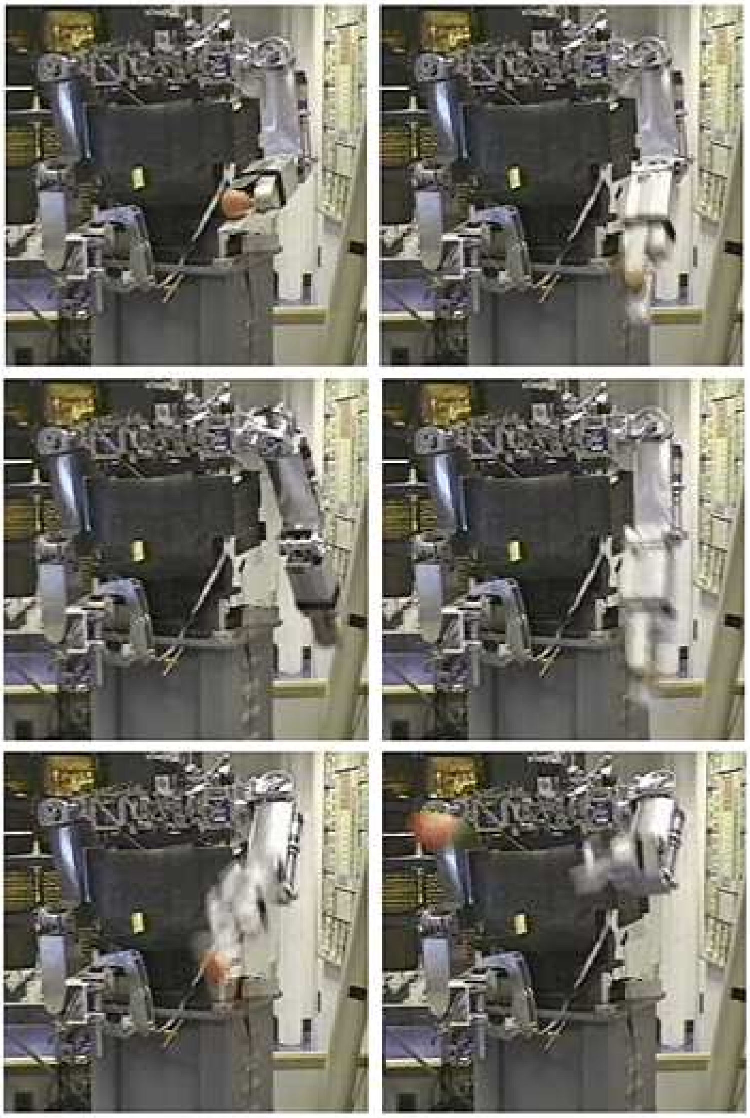

Figure 7-13: $\boxed{\text{REAL}}$ Series of stills from sequence of the arm throwing a ball. The picture sequence is left to right and then top to bottom. The overall time of the throw is about 1.2 s, although these pictures are not equally spaced over that time. The arm holds the ball up, swings the elbow and shoulder back, and then swings the straight arm forward and releases the ball.

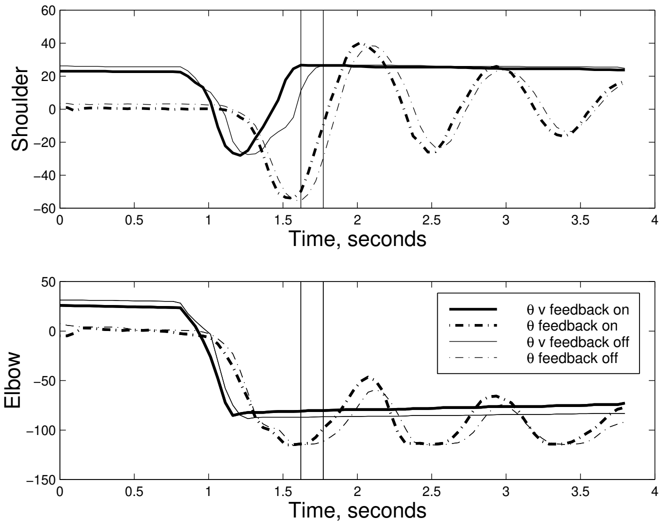

Figure 7-14: $\boxed{\text{REAL}}$ Plot of joint angles (θ) and setpoints (θ_v) during throwing. Two cases are plotted, using thick lines indicate when feedback is on, and thin when it is off. The plots show the shoulder moving back and forward and the elbow moving straight back. Some photographs of this motion are shown in figure 7-13. The ball is released at the end of the shoulder motion, as indicated by the vertical lines, although the ball does not actually leave the hand until about 0.5 seconds later. The most obvious effect of the feedback is to increase the speed of the setpoints to the joints (solid lines), and thus change the speed of the arm. The feedback also makes the hand release earlier in the motion, which throws the ball forward rather than up.

The postures of the arm were chosen to be similar to a human action. The arm starts holding the object up, then the elbow is driven back using a step command, and the shoulder back and forward using a pulse. This has the effect of swinging the arm back firmly, so hyperextending the shoulder joint, and storing energy in the shoulder spring. The arm comes forward straight and releases the object. Since the robot has no hand, the object is gripped between the wrist and a sheet of metal attached to the forearm. The wrist releases grip when the shoulder oscillator has finished its pulse.

The effect of the feedback on the throwing action is not very great, at least for the example throw shown in figure 7-14. The feedback makes the arm move faster, and also releases the object earlier in the throw. When using feedback, the wrist starts to release the ball when the arm is extended all the way back, but the ball is carried by the hand and not actually thrown until some time later (see photographs in figure 7-13). Without feedback, the ball is released much later. Releasing earlier may give a better follow through on the throw, and contributes to throwing forward rather than up.

In any case, the effect of the feedback is not large. One might expect it to be greater, and this is an area for further work. The oscillator's ability to quickly adapt to the dynamics of the arm might make it particularly appropriate for throwing tasks, by adjusting automatically to the mass of the object. Work by Bingham et al. (1989) suggests that humans heft objects to determine their properties before tuning the stiffnesses of their arms to achieve a powerful throw.

Throwing objects is sensitive to the release of the object, which was somewhat arbitrary in this implementation. Even a good swing can produce a poor throw if the release is fumbled. An overarm throw was also implemented, using four joints of the arm, with a sequence shown in figure 7-15. For this case, the shape of the hand was redesigned to give a better throw.

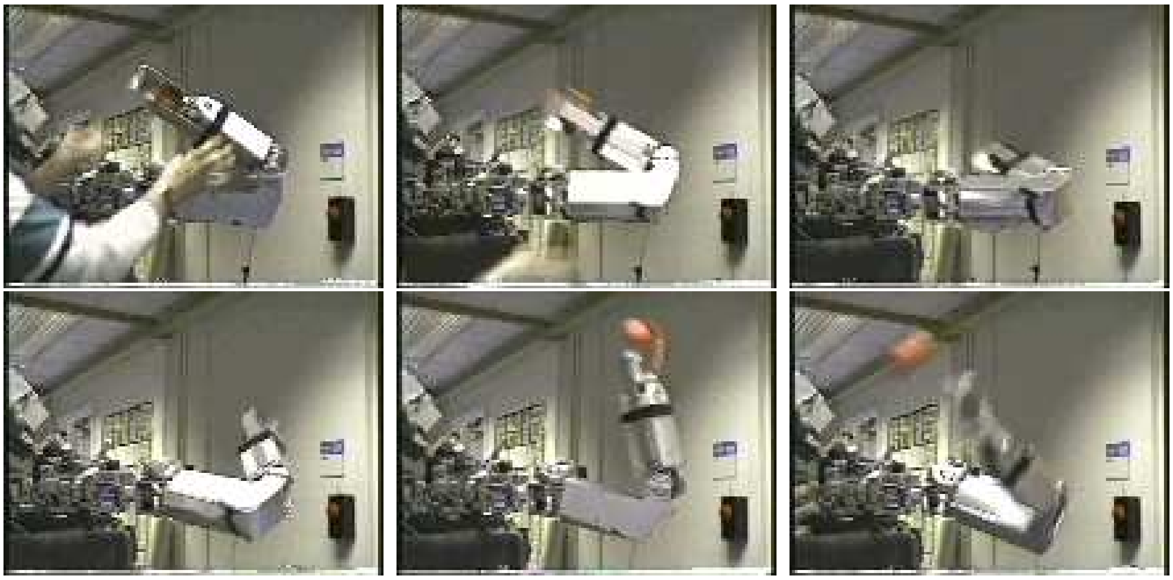

Figure 7-15: $\boxed{\text{REAL}}$ Overarm throw sequence, with pictures taken every 0.2 seconds. The sequence goes from left to right and top to bottom. Two shoulder joints and two elbow joints are used to produce this motion, all activated with pulses except for one elbow joint which was driven using a step. Throwing is sensitive to the release of the object, and in this case a redesigned hand was used to improve the throw.

7.4 Hitting

The task of hitting or hammering requires a similar motion to throwing but avoids the difficulty of releasing the object. Two applications are described here, with the robot hitting a "punchbag" and hammering a nail. These motions exploit the natural dynamics of the arm, using energy stored in the arm springs and gravity to produce effective hitting. They also exploit the ability of the arm design to withstand considerable shock loads.

The punchbag was constructed to measure the energy transfered from the arm to the target for tuning purposes. It consists of a rubber ball on a sprung boom. When the arm hits the ball, it causes the boom to rotate against the spring. By measuring the maximum deflection of the boom, the energy of the impact can be determined.

Figure 7-16 shows a sequence from the oscillator hitting the punch bag. The elbow and shoulder are activated by oscillators with the wrist having a low stiffness. The energy stored in the wrist is visible in the lower left frame, it being swung back by the action of lifting the arm, before rebounding onto the punchbag. The hitting action is much stronger when the arm is lifted up and then down, rather than just going down, due to this extra stored energy. The hit is also more powerful when the wrist stiffness is low, the mass of the hand acting like a hammer.

Figure 7-17 shows the shape of the hitting motion in the vertical plane, computed by using the joint angles and an approximation to the forward kinematics of the arm. When the feedback is on, the arm is moved up and then directly down to hit the punchbag (represented by the black rectangle). Without feedback the motion is more curved and much slower (the arm is drawn at 0.02 second intervals). This is shown more clearly in figure 7-18 which plots the height of the hand against time. The position of the punchbag is shown with the horizontal line, and the increased speed at impact is apparent.

The same configuration was used to hammer nails into wood, as shown in figure 7-19. Unfortunately no visual guidance was used so careful alignment of the nail with the hammer was required!

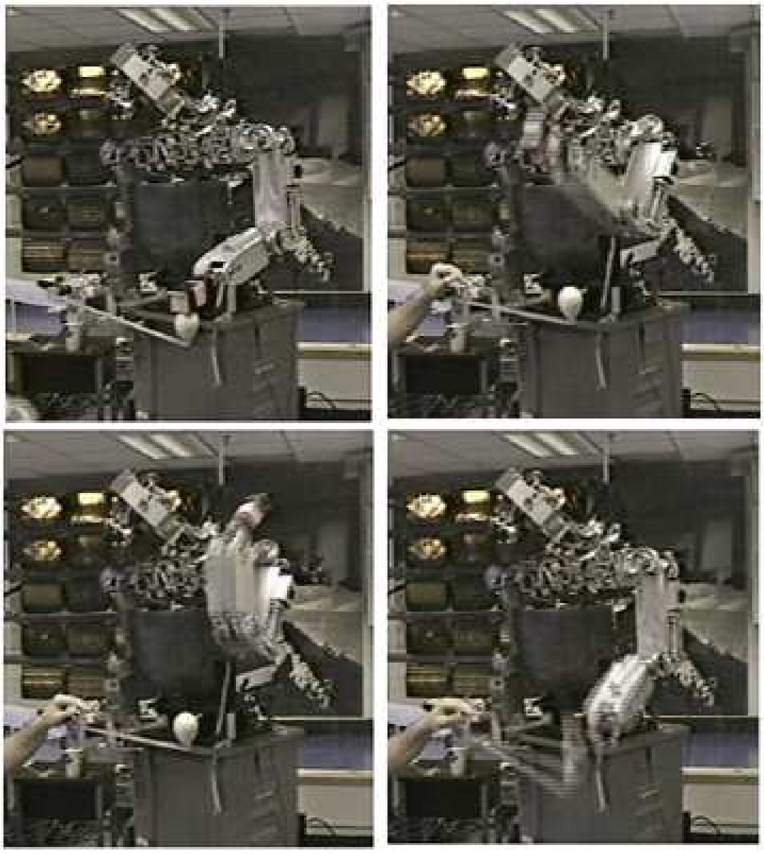

Figure 7-16: $\boxed{\text{REAL}}$ Four stills from a video of the robot hitting the punchbag. The sequence goes from left to right and top to bottom. The arm starts resting on the punchbag, and is raised up as shown at the top. The arm whips down, overextending the wrist joint (bottom left) and hitting the target powerfully. The shock tolerance of the arm is exploited to produce this movement without damage.

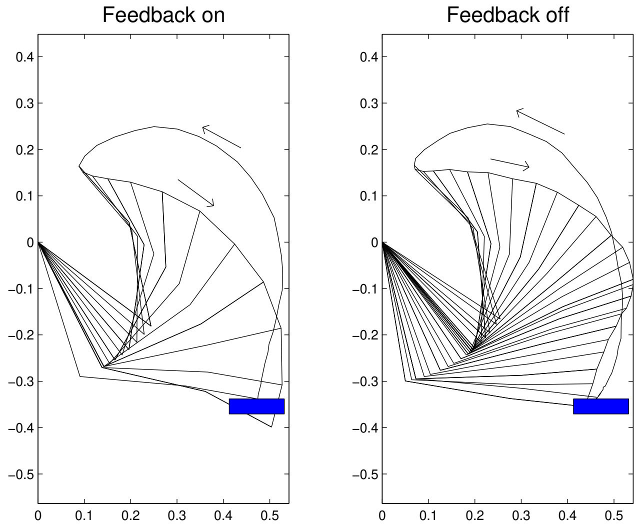

Figure 7-17: $\boxed{\text{REAL}}$ Motion of the arm in the vertical plane during hitting. The target is the punchbag which is indicated by the rectangle. The trajectory of the hand is marked, together with the position of the arm at 0.02 second intervals on the downward stroke. In the left hand graph, feedback is used and the arm moves faster and more directly to the target, as opposed to the non-feedback case in the right hand graph. The hyperextension of the wrist and its contribution to the hitting is also apparent when feedback is used.

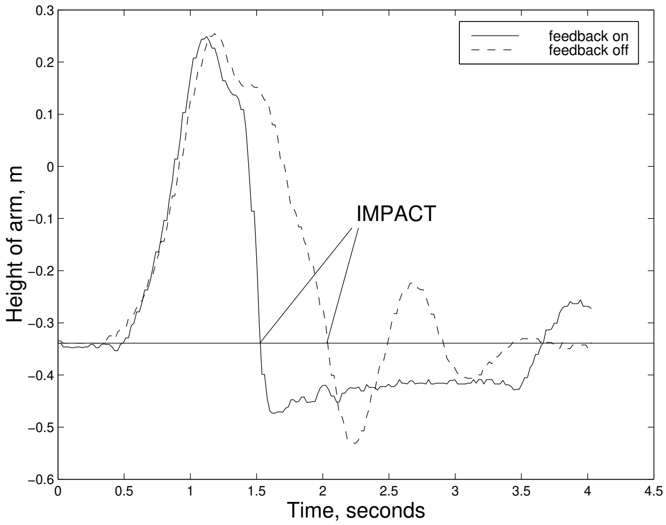

Figure 7-18: $\boxed{\text{REAL}}$ Graph of the height of the hand plotted against time for hitting the punchbag. The full trajectory is shown in figure 7-17. The hand moves up at about the same speed regardless of the feedback, but with feedback it accelerates down rapidly, with a much higher speed at impact (where the lines cross the starting height, marked by the horizontal line). The impact does not affect the arm motion a great deal because the inertia of the punchbag is small, and because it is sprung and so presents a small resisting force.

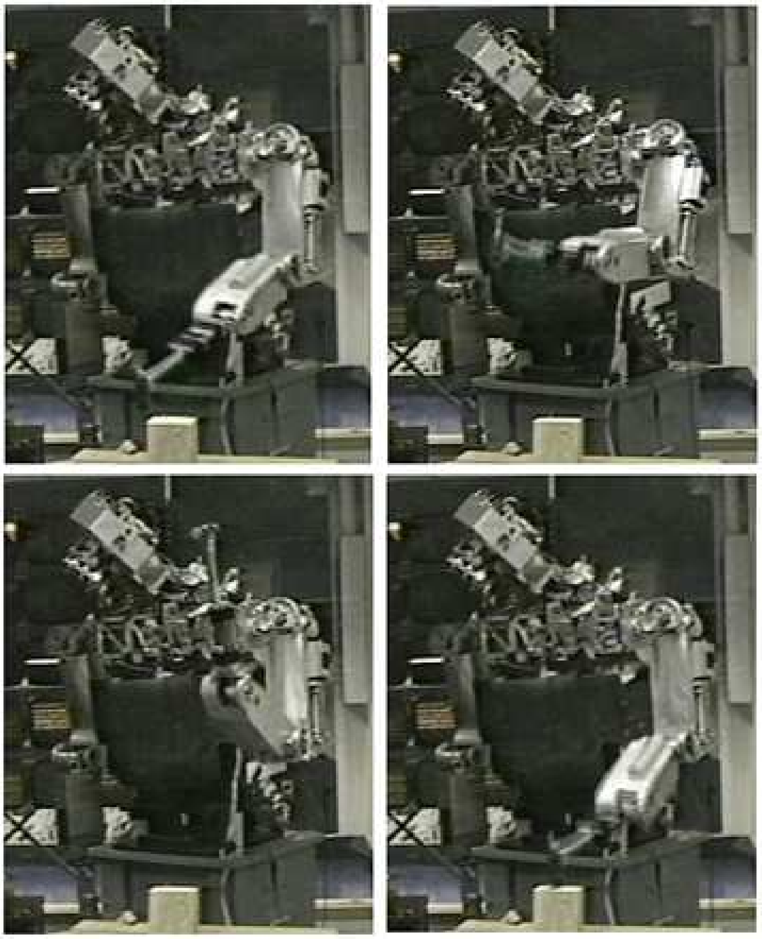

Figure 7-19: $\boxed{\text{REAL}}$ Four stills from a video of the robot hammering a nail. The sequence goes from left to right and top to bottom. The elbow and shoulder joints drive up and down to give a powerful hit with the hammer. The motion causes the hammer to be swung fairly high, and extend the wrist joint (lower left picture). This stored energy is then released into the nail (lower right).

The arm swings the hammer up, storing gravitational potential energy in the hammer, and storing energy in the springs of the arm. These are both released into the nail.

As with throwing, the effect of the feedback is predominately that of changing the speed of the motion, which could easily be achieved by using a pulse with no feedback. The oscillator does make the motion faster, which is the correct action for both tasks. Anecdotally the feedback was useful from a safety point of view. If the arm was restrained, the oscillator was affected by the feedback from the slowly moving arm, causing it to drive the arm in a less violent manner. As with the throwing task, more research is needed to elucidate the effect of the feedback, and determine whether it is useful.

7.5 Conclusion

This chapter has shown that the oscillators are versatile, and can be used for a wide range of tasks, both rhythmic and discrete, and use other sensory modalities to provide feedback and entrainment.

The oscillator solutions in these examples are all adaptive, altering the drive to the arm depending on the motion of the arm, or in the case of the drumming, the sound created by the arm. For the discrete tasks the nature of adaptation is not very clear, although it appears to have roughly the right effect. The feedback causes the arm to move out and back faster, so creating a more powerful throw or a more powerful hit. The effect of the feedback is more clear for the drumming, allowing the arm to synchronize with an external beat, and create a stable drumming rhythm.

The drumming example shows the simplicity of exploiting the natural dynamics of the system for a complex task. The arm synchronizes with an external beat because the sound of that beat and the arms own drumming are combined by being heard by the same microphone. The synchronization occurs even though the overall system is not calibrated, has unknown delays and uses a low gain controller to move the arm. It is synchronized because hitting in phase is the limit cycle solution of the auditory-motor loop set up by the oscillators. The system requires the delays and low stiffness in order to work, which reduces the pressure on making efficient auditory processing or having high bandwidth connections between the system processors.

The examples also illustrate the ease of implementation of the oscillators for these tasks. The oscillators can entrain with a range of input signals, and are robust to changes in the parameters. Once the input gain is large enough that the system is entrained, changing it has little effect on the overall system. The method of inhibiting the auditory signal when it is not expected is another simple and robust method to obtain complex behavior.

The particular implementation of the arms uses a number of processors with low bandwidth communication between them. The entrainment properties of the oscillators make them appropriate for this distributed system, and more robust than attempting to create a synchronized global clock.

Finally, it is interesting in the drumming example that the two phases that were easy to create were in phase and out of phase. These were made by simply flipping the sign of a feedback signal, and modifying the auditory input. Humans also appear to find these phases easy to produce, and others more difficult. There is considerable literature (e.g. Haken et al. (1985), Kay et al. (1987)) which shows that humans have a preference for these phases. The preference varies with frequency, with out of phase motions being only possible at low frequencies, and in phase motions possible at all frequencies. It would be interesting to explore the frequency dependence of the oscillator system from this respect.

Chapter 8

Conclusion

8.1 Further work

There are many topics arising from the thesis which deserve further study. These include:

- **Complex timing constraints.** There exist tasks which fit into the general framework exploited by the oscillators but which have complex timing constraints. For example, consider the cases of a Yoyo and a Slinky toy. Both exert forces on the arm, and in both cases the steady state motion requires coordination between these forces and the arm motion. This suggests that the oscillator solution should work well. While the oscillators work well with the Slinky, they do not appear to work with the Yoyo. This is because the coordination required of the arm is more complex and dependent on timing for the Yoyo case. This is true both in steady state, and particularly in the startup transient. Extending or manipulating the timing of the oscillator system would allow it to perform tasks with complex timing constraints.

- **Potential fields.** The idea of applying potential fields to the arm was mentioned in chapter 5 and deserves further study because the work was restricted to a simple example due to hardware and time limitations. One interesting aspect of the potential field is that it need only be strong enough to cancel the undesirable natural dynamics of the arm. This means that it need not be stiff (which facilitates implementation) and need only be specified where necessary. This makes it particularly appropriate for incremental learning through imitation. One might envisage a system where a human guides the arm through a desired motion, and then corrects the motion as the robot repeats it. The correction would be implemented by increasing the strength of the field locally, so constraining the arm motion at that point. Learning by imitation has recently become an intensive field of study because it promises to provide simple and flexible ways to control robots. Recent examples include Miyamoto et al. (1996), Miyamoto and Kawato (1998), Brooks et al. (1999) and Schaal (1999). The robustness and ease of implementation of the oscillator systems should make them appropriate for imitating rhythmic and dynamic discrete tasks.

- **Sequences and compound motions.** One problem not addressed in the thesis is how to switch among a number of oscillators to produce compound motions or sequences. This is another possible method to increase the complexity of tasks that are possible using oscillator control. Switching between controllers raises a number of interesting questions:
  - How should the oscillators be synchronized across the switch? and is that necessary?
  - When should the switch be made? (after a certain amount of time, or dependent on the state)
  - How should the subcontrollers be designed?
  - Will the final system be stable?

There is theoretical work on hybrid systems (e.g. Branicky (1994)) which is relevant here. One robotic example which combines switching and exploiting the natural dynamics is the work of Kuniyoshi and Nagakubo (1997) where a simulated humanoid was controlled to stand up from a supine position using a sequence of simple controllers.

- **Discrete motions.** The oscillator behavior for single motions was described in chapter 7. An analysis method analogous to the describing function analysis developed for the rhythmic case is required to gain improved insight into the discrete behavior. This would hopefully shed light on the exact role of the feedback in these motions. One idea for an evaluation criterion is to determine the energy imparted to a robot link by a single cycle of the oscillator. This could then be compared to the optimal pulse, given the system stiffness and inertial properties.
- **Theoretical questions.** The theoretical results in chapter 6 indicate that many questions concerning the oscillators remain unanswered. These include results on the classes of systems that have limit cycle solutions when driven by oscillators and the global or semi-global stability of these limit cycles. The oscillators are a compelling system for further study in this respect. They exhibit a range of interesting behaviors, their piecewise-linear dynamics open them to a range of techniques, and any new theoretical results will have an impact on the practical design of systems.

8.2 Vision

This thesis has demonstrated an exciting range of tasks with a simple control system. While it has demonstrated the power both of exploiting natural dynamics and using oscillators to control arms, the method has a long way to go to reach the kind of versatility and flexibility of actions that humans routinely demonstrate. This section considers how to create that kind of performance, considering other ways to exploit the arm dynamics, exploiting the arm statics, tidying up details, and looking at the problem of learning.

- **Generalization.** This thesis has argued strongly for exploiting natural dynamics using the Matsuoka oscillator. This approach, while perhaps surprisingly versatile, is limited due to the dynamics of the oscillator. To achieve anything like human versatility other controllers and control methods need to be explored. Investigating other controllers which exploit natural dynamics should open up a variety of different tasks, for example discrete motions, slow motions, compound rhythmic motions, or asymmetric motions.

  This thesis has concentrated on exploiting the resonant properties of the arm, when there are other aspects of natural dynamics which can be exploited to give wider ranges of tasks. These include the use of the skeleton for load carrying, and also the use of internal inertia for explosive tasks (as in the work of Brown (1994)).

  Generalizing the ideas in this thesis to other controller types which can exploit the natural dynamics, as well as generalizing to other aspects of the robot dynamics should give greater versatility.
- **Exploiting task statics.** All the applications in this thesis are dynamic tasks, where precise motion is not required. Humans are generally skilled both at dynamic motions and precise manipulation tasks, such as threading a needle, sewing, writing, or peeling potatoes.

  For these tasks the static behavior of the arm is more important than its dynamical behavior. The static properties of the arm such as its stiffness, whether it is braced to remove excess degrees of freedom, and whether the active degrees of freedom are aligned with the task can all be exploited to simplify the control required. The sensory modalities for these tasks are also different from the dynamic case, relying more on touch, force and vision sensing. These different sensory modalities might have to be applied in different ways to modify the arm behavior.

The questions of how arm properties can be exploited for precise tasks, and how the sensory feedback should be used are challenging. Any progress towards performing these tasks with the same robustness and computational simplicity as the work in this thesis would be an exciting step forward. It would also greatly increase the versatility of robots.

- **Details.** Most of the work in this thesis ignores the details of arm control which would be needed for a flexible working system. A good example of this is starting and stopping the oscillators cleanly. This was not considered during the thesis but could be important for some tasks. A complete system would need details of this kind to be worked out more carefully.

- **Programming/learning.** The combination of arm and task dynamics is complicated, particularly if a wide range of tasks are considered. For the final system to be versatile and flexible it is inevitable that some learning will be required. This raises the questions of what should be learned and how should it be learned. While these specifics remained to be worked out, the type of tuning used in this thesis is a good model. Static parameters were tuned which determined a complete dynamic behavior, with the oscillator behavior reducing the complexity of the learning problem (by automatically being coordinated with the task). In addition the parameters themselves were easy to set, with good performance for a wide variety of parameter settings. While not all learning problems will be so straightforward these characteristics make the learning easy and so are worthwhile to bear in mind.

  One of the major issues will be learning and scaling the complexity while retaining the useful properties of exploiting natural dynamics. This issue was touched on in chapter 5 where two different methods of connecting oscillators had rather different robustness properties.

  Attacking the learning issue should shed light on how to increase the complexity of the robot behavior. Questions which are relevant here are the role of imitation in teaching the robot new tasks, and perhaps the role of memory and internal models in remembering and applying previously learnt behaviors to new situations. The transfer of skills to different parts of the workspace, to different arms and to different tasks is also important. Thinking of these questions in the context of exploiting natural dynamics may facilitate finding answers. For example, transfer of skills may only be useful if the underlying dynamics are similar.

8.3 Summary

This thesis has presented an approach to robot arm control which exploits natural dynamics. The approach uses a a set of simple non-linear oscillators to drive the joints of a compliant arm. The oscillators use feedback to adjust their commands relative to the actual joint motion, and so tune into the arm's natural dynamics.

Chapter 3 introduced the oscillator and described its behavior when coupled to single degree of freedom systems. This behavior is generally coordinated with the motion of the system and robust to system and oscillator parameter changes. An analysis method using describing functions was described which is accurate and powerful; it enables detailed design of oscillator systems by predicting their behavior. It can also be used to explain the inherent robustness of the oscillators. The design tool is simple and easy to apply. It enables other researchers to understand, design and compare oscillator solutions to other approaches.

The oscillator robustness properties carry over to the multiple degree of freedom tasks which were considered in chapter 4. Using mechanical coupling between the oscillators as opposed to any explicit connections, the oscillators find and drive the system in its resonant mode, automatically adjusting themselves relative to the task. This is both remarkable and useful. It is remarkable that independent control at the joints can give such complex coordinated behavior of the whole arm. It is also remarkable that this works when the arm is redundant, with more than one arm, and when the coupling is fairly weak, as in the Slinky toy example. This property is useful because a variety of tasks are defined as resonant modes of the arm system.

The robustness of this system is also compelling. Most of the parameters can be changed by factors of three without changing the overall performance. This makes tuning parameters trivial. The oscillator natural behavior removes the need to specify coordination between the joints, which makes tuning easier still, because there are less parameters to tune.

Not all tasks are conveniently specified by the resonant mode of the mechanical system and chapter 5 considered methods to extend the oscillator system to some of those cases. The main difficulty is retaining the robustness and self-organizing properties of the oscillators while influencing their final behavior. The chapter showed that coupling the oscillators through the natural dynamics was more robust and more powerful than connecting the oscillators into networks. This result is a compelling argument for exploiting natural dynamics.

Chapter 6 returned to the issue of analysis first raised in chapters 3 and 4. It presented a variety of theoretically exact results and tools for predicting the final behavior of oscillator driven systems. These methods together with the earlier results provide a powerful set of tools for understanding the behavior of oscillator driven systems.

Chapter 7 discussed various applications of the oscillator system. The chapter showed that the oscillators can produce both discrete and rhythmic motions. The oscillator system is generally easy to use. The parameters are easy to set and the feedback gives powerful and sensible behavior. It is indicative of the merits of the oscillators that all the tasks in the thesis were accomplished with the same oscillator architecture. The only changes were adjustments to the posture of the arm, the sizes of the joint commands, and the object attached to the robot's hand.

To conclude; the approach taken in this thesis of exploiting the natural dynamics of the arm using non-linear oscillators has been shown to work well in a number of respects. The approach can be applied over a wide range of discrete and rhythmic tasks, is robust and is easy to implement. These results suggests that the general approach of exploiting natural dynamics is a powerful method for obtaining coordinated dynamic behavior for robots.

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