Timing and coordination

Gregor Schöner
so far…

- … we have studied the generation of movement in vehicles…
- through a “behavioral dynamics” that is in closed loop with the environment
- as it takes (possibly time varying) constraints from the perceived environment
- and expresses these as contributions to the dynamics…
- whose attractor solutions then generate movement plans…
.. now we will look at

- how movements can be generated in open loop, that is, from an internal “neural” dynamics

- this serves primarily to generate movements that are “timed”, that is,
  - they arrive “on time”
  - the are coordinated across different effectors
  - the are coordinated with moving objects (e.g., catching)

- timing implies some form of anticipation…
How is timing done in conventional robotics?

- **classical fixed control:** fixed templates of timing encoded in digital computers… determined from trajectory planning algorithms that a purely kinematic, and are realized by servo-controllers that “track” the time plan.

- **advanced control:** the planning takes the physical dynamics into account (e.g. optimizing a cost function).
Timing in autonomous robotics

Koditschek’s juggling robot:

- physical dynamics of bouncing ball modeled... actuator inserts a term into that dynamics so that a periodic solution (limit cycle) results.

- ball is kept within reach by conventional P control from contact to contact.
Timing in autonomous robotics

Raibert’s hopping robots

dynamics bouncing robot modeled… actuator inserts a term into that dynamics so that a periodic solution (limit cycle) results

robot is kept upright by controlling leg angle to achieve particular horizontal position for Center of Mass
How is timing done in conventional robotics?

- Raibert’s bio-dog expand that idea by coordination among limbs

https://www.youtube.com/watch?v=M8YjvHYbZ9w
Timing in nervous systems

- External perceptual contribution to timing
- External mechanical contribution to timing
- Absolute timing
- Coordination: relative timing
- Biomechanical contribution to timing
Relative vs. absolute timing

Relative phase = $\frac{DT}{T}$
Absolute timing

- examples: music, prediction, estimating time
- typical task: tapping
- self-paced vs. externally paced
human performance

- on absolute timing is impressive
- smaller variance than 5% of cycle time in continuation paradigm

[FIG. 3. Variability of timing. At longer intervals, timekeeper variance ($\text{var}(C)$) increases but motor implementation variance ($\text{var}(M)$) is relatively constant. (From Wing, 1980.)

It is instructive to relate the partitioning of variability of timing into timekeeper and motor implementation variance in repetitive responding to measures of timing variability reported in a single interval production task studied by Rosenbaum and Patashnik (1980a, 1980b). Subjects used R and L index finger responses to delimit a single interresponse interval, $I$, to match a previously presented target, $T$. This was varied in steps of 100 ms up to 1000 ms, with the shortest, $T/1000\text{ms}$, requiring simultaneous movement of the index fingers. Instructions in different blocks of trials emphasized either speed (produce the first response as quickly as possible) or accuracy (produce the interval as accurately as possible). As would be expected, reaction time (RT) was faster in the speed condition. RT was also faster with larger values of $T$. Later, we return to consider these RT effects, but here we focus on the interval timing results. In both speed and accuracy conditions mean($I$) matched the target. For $T/1000\text{ms}$ the variances were nonzero and equal in the two conditions. At larger values of $T$, var($I$) increased linearly with mean($I$). The slope of the function relating mean and variance of the intervals between left- and right-hand responses was less steep in the accuracy condition than in the speeded condition (see Fig. 4).

There are two points to note arising from the results on variability of the time intervals produced in this task. First, in the condition calling for simultaneous responses, the variability var($I$) may be attributed to the motor system, since there is no demand on timing ($T/1000\text{ms}$). It is thus reassuring to note that Rosenbaum and Patashnik reported equal intercepts (no difference in the variability at zero interval). [Wing, 1980]
Theoretical account for absolute timing

- (neural) oscillator autonomously generates timing signal, from which timing events emerge

- => limit cycle oscillators

- Clocks=limit cycle oscillators
Limit cycle oscillator: Hopf

normal form

\[
\begin{pmatrix}
\dot{x} \\
\dot{y}
\end{pmatrix} = \begin{pmatrix}
\alpha - \omega \\
\omega & \alpha
\end{pmatrix} \begin{pmatrix}
x \\
y
\end{pmatrix} - (x^2 + y^2) \begin{pmatrix}
x \\
y
\end{pmatrix}
\]

\[
x = r \cos(\phi) \\
y = r \sin(\phi)
\]

\[
\begin{aligned}
\dot{r} &= \alpha r - r^3 \\
\dot{\phi} &= \omega
\end{aligned}
\]

\[
x(t) = \sqrt{\alpha} \sin(\omega t)
\]

amplitude \(A = \sqrt{\alpha}\)

cycle time \(T = \frac{2\pi}{\omega}\)
A periodic evolution of an activation variable cannot be obtained as a solution of a single-variable dynamical system, because most levels of activation (here the zero level) are crossed in two different directions, so that the future is not uniquely determined by the present state of the activation variable. To see this, imagine a periodic time course of activation (Fig. 5). All levels of activation (except at the turning points) are then passed through in two directions, once at increasing and once at decreasing activation. Thus, such activation values do not uniquely specify the future. A second variable, here called ''inhibition,'' is needed, to disambiguate the future: each activation level is passed through once at a smaller and once at a larger level of this second variable. Thus, clocks cannot be built as dynamical systems in terms of activation alone!

Stable periodic solutions, to which the system is attracted from nearby states are called limit cycle attractors. An example of a dynamical system supporting limit cycle attractors of an activation–inhibition pair of variables is

$$\tau \dot{u} = -u + h_u + w_{uu}f(u) - w_{uv}f(v)$$
$$\tau \dot{v} = -v + h_v + w_{vu}f(u),$$

Equations first analyzed by Amari (1977). The first two terms of each equation describe two linear uncoupled dynamical systems, each with a stable fixed point at the resting levels of activation, $h_u$, and of inhibition, $h_v$. A sigmoid function, $f(u)$, makes the system nonlinear in terms of ''self-excitation'' ($w_{uu}$) and of coupling between activation and inhibition variables ($w_{vu}, w_{uv}$). For appropriate choices of these parameters, a limit cycle attractor emerges (Fig. 6). The stability of the periodic solution manifests itself by attraction of neighboring states toward the limit cycle. The activation-based stochastic timer model emerges as the limit case, in which the vector field is structured such that a period of graded activation growth is followed by a more rapid phase of activation decay (Fig. 6b). In fact, abstractly speaking, any clock is a limit cycle attractor of a dynamical system (see, e.g., Andronov, Vitt, & Khaikin, [Amari 77].
Neural oscillator accounts for variance of absolute timing

[Schöner 2002]
Clocks

- hour glasses are also oscillators
- but: it is critical to include the “resetting”

[from: Schöner, Brain & Cogn 48:31 (2002)]
Reduced timing variance for bimanual movement observed by Ivry and colleagues accounted for by averaging of two times but: requires coupling.
Relative timing: movement coordination

- locomotion, interlimb and intralimb
- speaking
- mastication
- music production
- ...approximately rhythmic
Examples of coordination of temporally discrete acts:

- reaching and grasping
- bimanual manipulation
- coordination among fingers during grasp
- catching, intercepting
Definition of coordination

- Coordination is the maintenance of stable timing relationships between components of voluntary movement.

- Operationalization: recovery of coordination after perturbations

- Example: speech articulatory work (Gracco, Abbs, 84; Kelso et al, 84)

- Example: action-perception patterns
Is movement always timed/coordinated?

- No, for example:

  - locomotion: whole body displacement in the plane
    - in the presence of obstacles takes longer
    - delay does not lead to compensatory acceleration

- but coordination is pervasive...
  - e.g., coordinating grasp with reach
Relative vs. absolute timing

Relative phase = DT/T

activation

threshold

dt

t

time

relative timing

absolute timing

relative phase = DT/T
Two basic patterns of coordination

- **in-phase**
  - synchronization, moving through like phases simultaneously
  - e.g., gallop (approximately)

- **anti-phase or phase alternation**
  - syncopation
  - e.g., trott
An instability in rhythmic movement coordination

switch from anti-phase to in-phase as rhythm gets faster

Kelso, 1984
Instability

- experiment involves finger movement
- why fingers?
  - no mechanical coupling
  - constraint of maximal frequency irrelevant
  - => pure neurally based coordination

Schöner, Kelso (Science, 1988)
Instability

- frequency imposed by metronomes and varied in steps
- either start out in-phase or anti-phase
data example (Scholz, 1990)
computation of continuous relative phase (Scholz, 1990)
Pattern stability

- instability: anti-phase pattern no longer persists

- thus: even though mean pattern is unchanged up to transition, its stability is lost

- => stability is an important property of coordination patterns, that is not captured by the mean performance alone
Measures of stability

- **variance**: fluctuations in time are an index of degree of stability

  - stochastic perturbations drive system away from the coordinated movement

  - the less resistance to such perturbations, the larger the variance
Measures of stability

- **relaxation time**
  - time need to recover from an outside perturbation
  - e.g., mechanically perturb one of the limbs, so that relative phase moves away from the mean value, then look how long it takes to go back to the mean pattern
  - the less stable, the longer relaxation time
data example
perturbation of
fingers and
relative phase

Scholz, Kelso, Schöner, 1987
Signatures of instability

- loss of stability indexed by measures of stability
relaxation times, individual data
data (averaged across subjects)  

Schöner, Kelso (Science, 1988)
Neuronal process for coordination

- each component is driven by a neuronal oscillator
- their excitatory coupling leads to in-phase
- their inhibitory coupling leads to anti-phase
Coordination from coupling

- coordination=stable relative timing emerges from coupling of neural oscillators

\[
\begin{align*}
\tau \dot{u}_1 &= -u_1 + h_u + w_{uu}f(u_1) - w_{uv}f(v_1) \\
\tau \dot{v}_1 &= -v_1 + h_v + w_{vu}f(u_1) + cf(u_2) \\
\tau \dot{u}_2 &= -u_2 + h_u + w_{uu}f(u_2) - w_{uv}f(v_2) \\
\tau \dot{v}_2 &= -v_2 + h_v + w_{vu}f(u_2) + cf(u_1)
\end{align*}
\]

Marginal stability of phase enables stabilizing relative timing while keeping trajectory unaffected.

\[ \frac{d\phi}{dt} = f(\phi) \]

Dynamical systems account of instability

- Coordination patterns are stable states
- Stability may vary and may be lost
- Instability leads to pattern change
Dynamical systems account of instability

- **state of dynamical system**
  - $x =$ relative phase

- dynamical system
  - $\frac{dx}{dt} = f(x)$

- fixed point, which is stable (attractor)
Dynamical systems account of instability

- at low frequencies this system is bistable

\[
\frac{dx}{dt} = f(x)
\]

in-phase  anti-phase
Dynamical systems account of instability

at increasing frequency, stability of anti-phase is lost.

rate of change of relative phase

- low frequency
- mid-range frequency
- high frequency

in-phase | anti-phase

relative phase

Graph showing the rate of change of relative phase with respect to frequency.
Predicts increase in variance

“critical fluctuations”
Predicts increase in relaxation time

“critical slowing down”

rate of change of relative phase

relative phase

increase in movement frequency

relaxation time

movement frequency
Conclusion

- to understand coordination patterns, we need to understand the underlying coordination dynamics
- = stabilization mechanisms
- and their strength
- from which the mean pattern emerges
What level does the instability of coordination come from?

- from peripheral motor control?
- from central motor control?
- from perceptual representations of movement?
What level does instability come from?

Is the instability tied to the motor system?

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Mechsner, Kerzel, Knoblich, Prinz, Nature 2001
Mechsner, Kerzel, Knoblich, Prinz, Nature 2001
coordination in space

- rather than in effector space
- so coordinated oscillators are central
- rather than peripheral
Coordination of discrete movement

coupling can account for coordination of discrete movement based on the idea that oscillator is “on” (stable) only for a cycle…

back and forth components of rhythmic movement are driven by different neural populations

so even rhythmic movement coordination may exploit this mechanism of discrete movement coordination

[Schöner, Biol Cybern 63:257 (1990)]
Robotic demonstration: timed movement with online updating
The vision system provides a prediction of the hitting point and the time-to-impact. At the end of the hitting movement sequence, the end-effector is still moving back to the reference configuration. This may for instance be reflected by an obstacle while the end-effector is still moving back to the initial posture. At the same time, the end-effector is still moving back to the initial posture. This may for instance be reflected by an obstacle while the end-effector is still moving back to the reference configuration.

In the second scenario (Fig. 7b) shows that the model is able to activate a new hitting sequence even while still reacting to an obstacle during the racket movement. This highlights the capability of the system in dealing with unexpected events during the hitting sequence. Both the hitting point and the time-to-impact are crucial variables for determining the success of the hitting sequence.

For a quantitative evaluation, we ran a trial in which the robot had to drive the ball up the inclined plane (without obstacles) as often as possible. The trial consisted of multiple sequences, and for each sequence, the number of consecutive hits among all sequences was recorded. For a steeper inclination of 10°, the success rate for hitting the ball was lower compared to a 5° inclination. The source code of the simulation is freely available for downloading at http://neuraldynamics.eu.
... deeper issue in timing...

- **contribution of the control level**
  - muscles and biomechanics contribute to timing

- **contribution of movement planning**
  - on line updating
  - arriving “just in time”

- **contribution of movement organization**
  - timed movement sequences
  - modulating timing in rhythms
  - coarticulation