Sensor Actuator Network

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SIGGRAPH 93

stochastic synthesis of controllers

sensory based - no state information

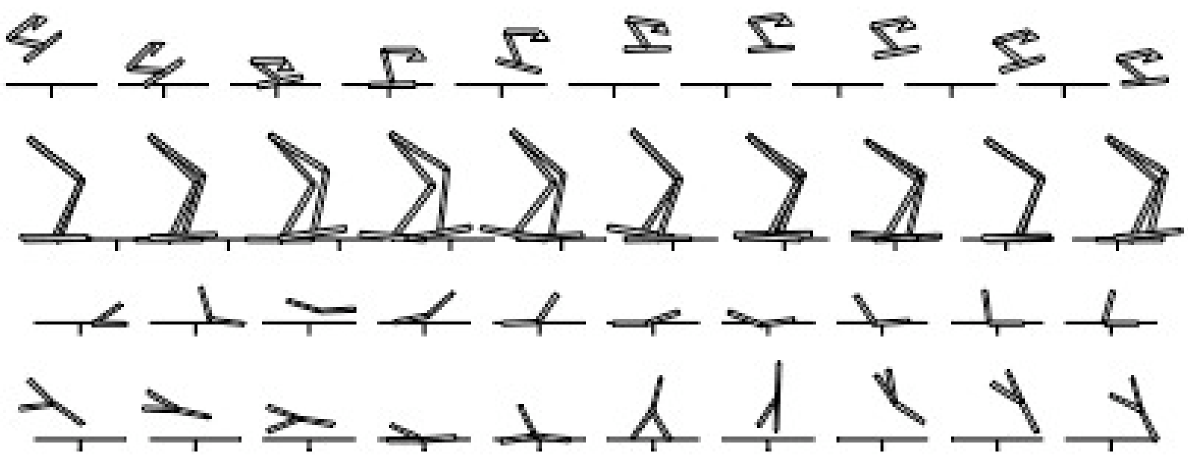


FIGURE 1. Some modes of locomotion using SANs

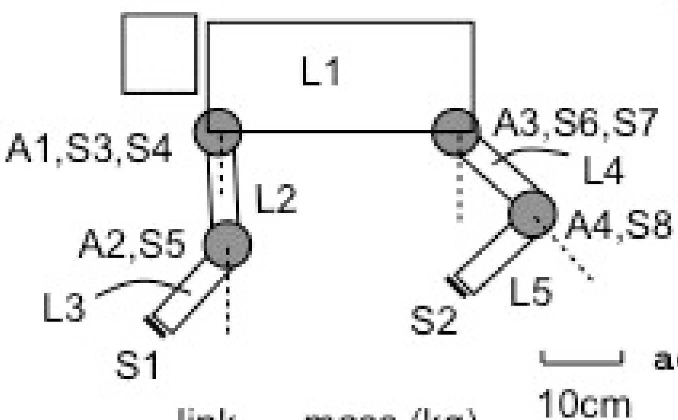
non-linear network of weighted connections
between a small number of binary sensors
and actuators (muscles)

internal delays - for dynamic properites

determine parameters to get desired behavior

generate and test

further optimization to refine controllers mechanical configuration:



link	mass (kg)
L1	1.0
L2	0.15
L3	0.10
L4	0.15
L5	0.10

sensors:

sensor	type	link	min	max
S1	touch			
S2	touch			
S3	angle	2	−180	−10
S4	angle	2	25	180
S5	angle	3	−180	−80
S6	angle	4	−180	42
S7	angle	4	55	180
S8	angle	5	−180	−105

actuators:

act.	min	max	ks	kd
A1	−20	30	0.4	0.01
A2	−85	−55	0.4	0.01
A3	40	55	0.4	0.01
A4	−110	−105	0.4	0.01

FIGURE 2. The bounder

planar dynamics in vertical plane

proportional-erivative controllers for forces & torques

binary sensor values

rigid links

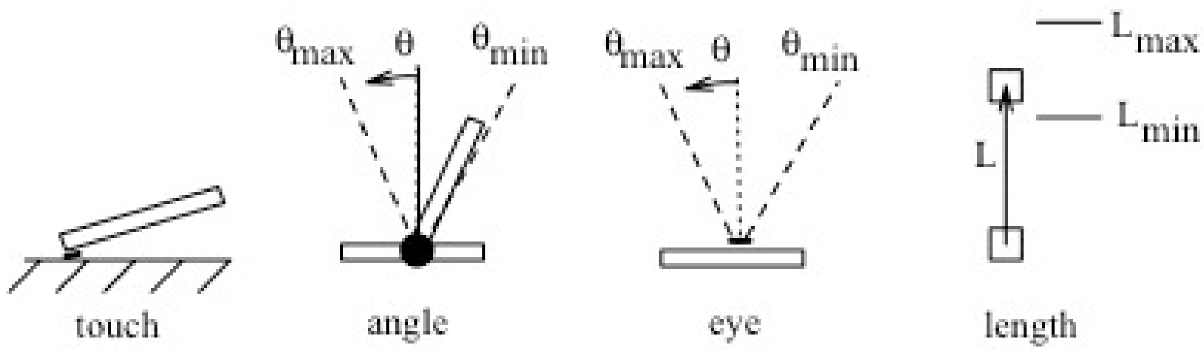


FIGURE 3. Sensor types

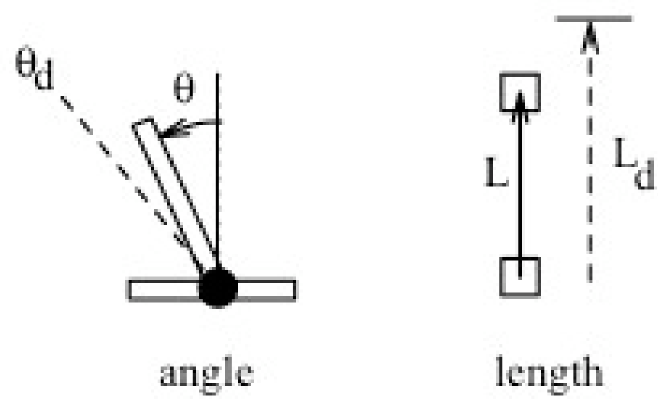


FIGURE 4. Actuator types

need fast dynamics simulator

creatures are free bodies in space

external ground forces use stiff spring & dampers

friction, wind, viscosity are used

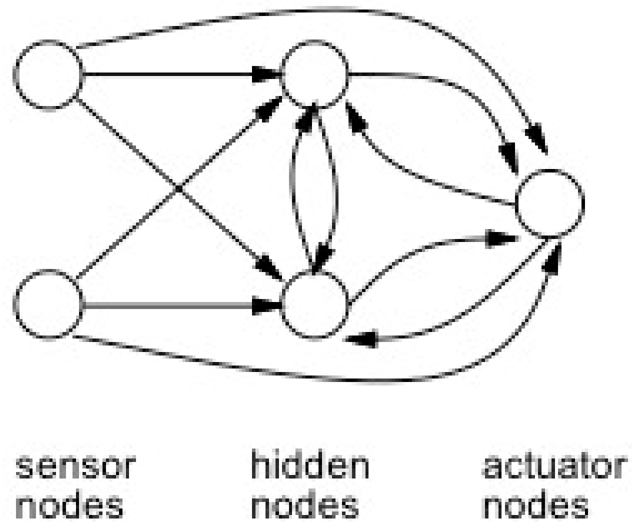


FIGURE 5. Topology of a sensor-actuator network

weighted connections in range -2:2

fully connected nodes

# of hidden nodes usually = # sensor nodes

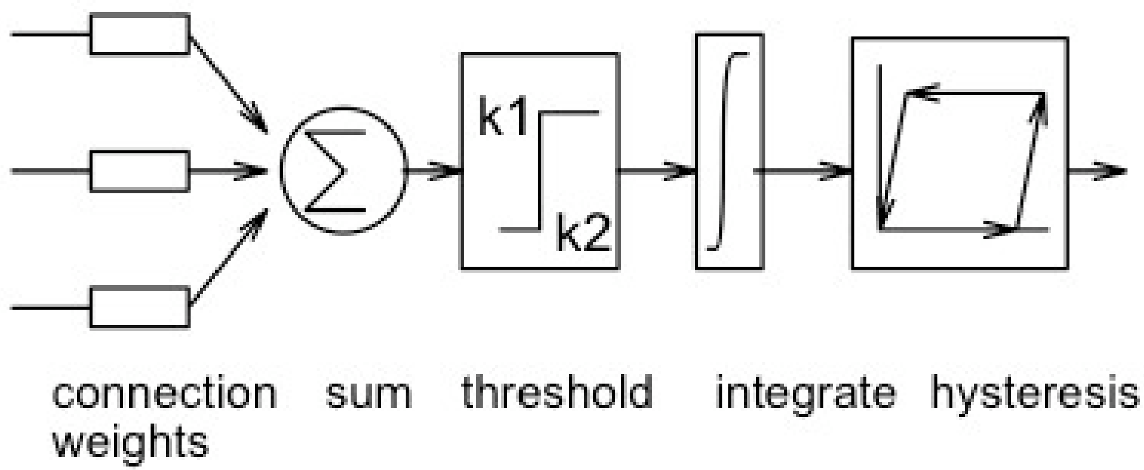


FIGURE 6. Function of a SAN node

time delay

fires '1' if weighted input is positive

```
sum = 0
for (each input i)
        sum = sum + input[i]*weight[i]
if (sum>0) then
        istate = istate + k1*dt
else
        istate = istate + k2*dt
if (istate>1.0) then istate = 1.0
if (istate<0.0) then istate = 0.0
if (output==1 and istate==0.0) then output=0
if (output==0 and istate==1.0) then output=1
```

FIGURE 7. Code corresponding to node function

Phase 1: random generate & test

evaluation metric
'distance traveled' for most examples

can incorporate other terms
average height
not falling over
tracking of a point-to-follow

Phase 2: Fine tuning

k1	delay in SAN node for turning on
k2	delay in SAN node for turning off
Amin	minimum desired angle or length for actuator
Amax	maximum desired angle or length for actuator
ks	spring constant for actuator
kd	damper constant for actuator
Smin	lower bound of sensing range for sensor
Smax	upper bound of sensing range for sensor

FIGURE 8. Adjustable parameters for SAN fine-tuning

non-linear

stochatic gradient ascent or simulated annealing

```
for (1000 trials)
        randomly choose a parameter to vary
        perturb the parameter value by +delta or -delta
        evaluate the new creature by simulation
        if (creature improved) then
                keep change
        else
                reject change
```

FIGURE 9. Pseudocode for stochastic gradient ascent

TABLE 1. The experimental creatures

creature	links	sensors	actuators	hidden nodes	speed cm/sec
crawler	4	8	2	10	11
fish	4	6	2	5	19
bounder	5	8	4	8	115
luxo	3	6	2	6	79
cart	2	6	1	5	23
walker	6	11	5	6	101
twolink	2	6	1	5	12
threelink	3	8	2	7	33
fourlink	4	11	3	8	55
star	3	8	2	7	9

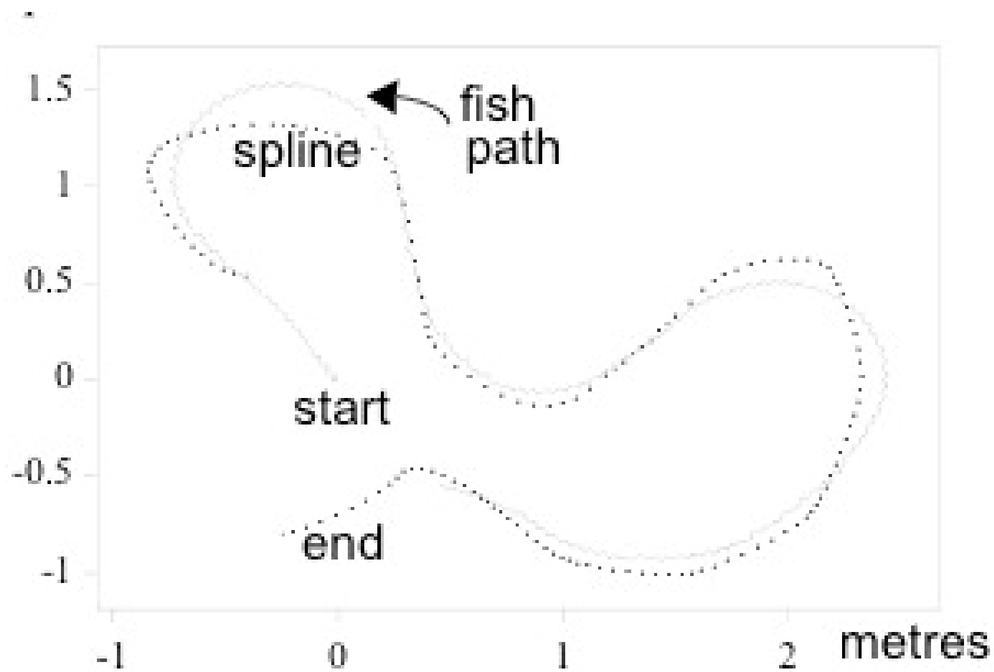
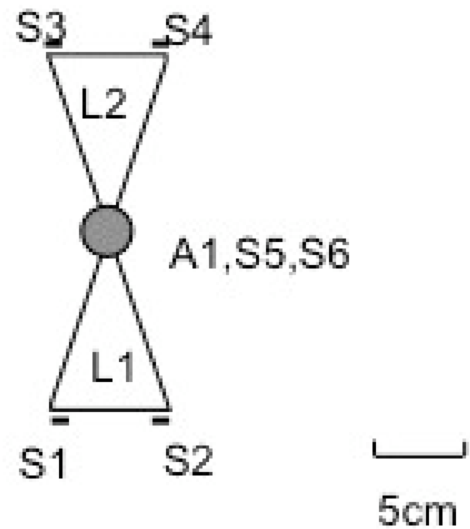


FIGURE 10. The fish chasing a point being dragged along a spline curve.

mechanical configuration:



sensors:

sensor	type	link	min	max
S1	touch	L1		
S2	touch	L1		
S3	touch	L2		
S4	touch	L2		
S5	angle	L2	−180	−120
S6	angle	L2	120	180

actuators:

act.	min	max	ks	kd
A1	−140	140	0.002	0.0001

link	mass (kg)
L1	0.10
L2	0.10

FIGURE 11. The cart creature

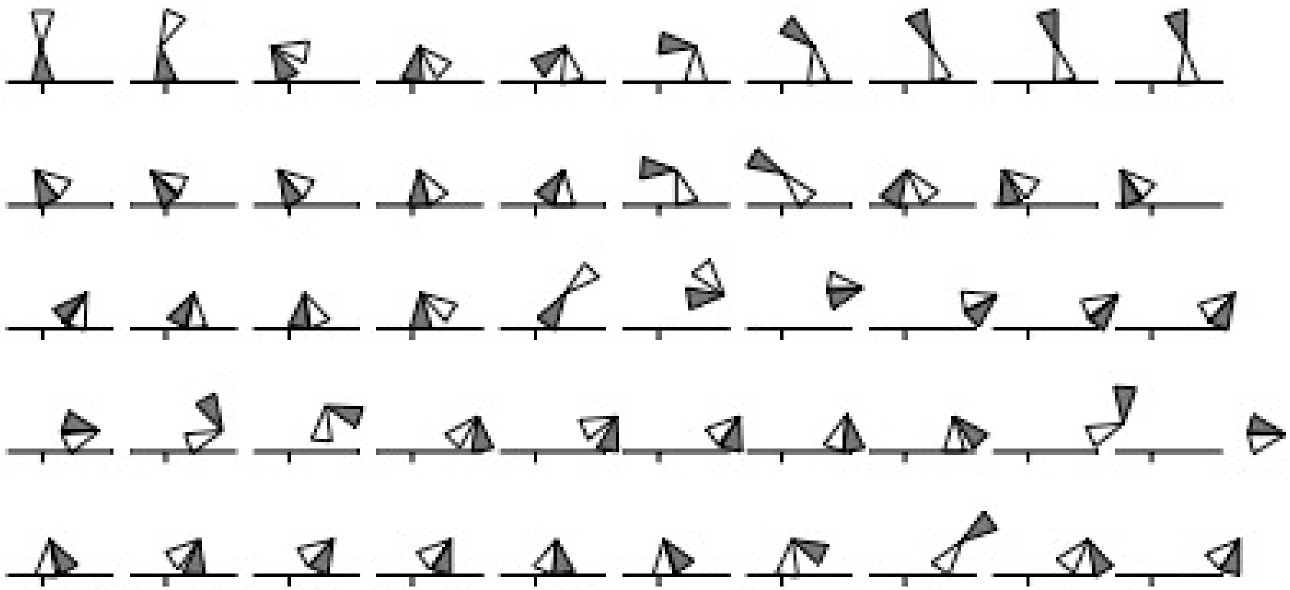


FIGURE 12. Modes of locomotion for the cart

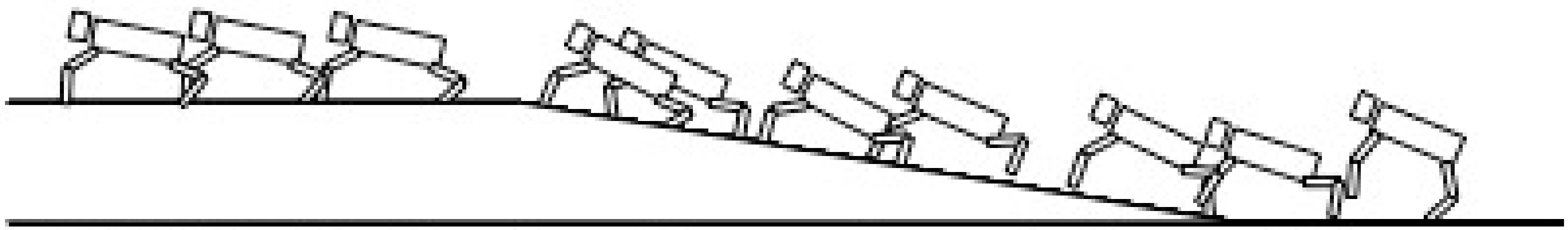
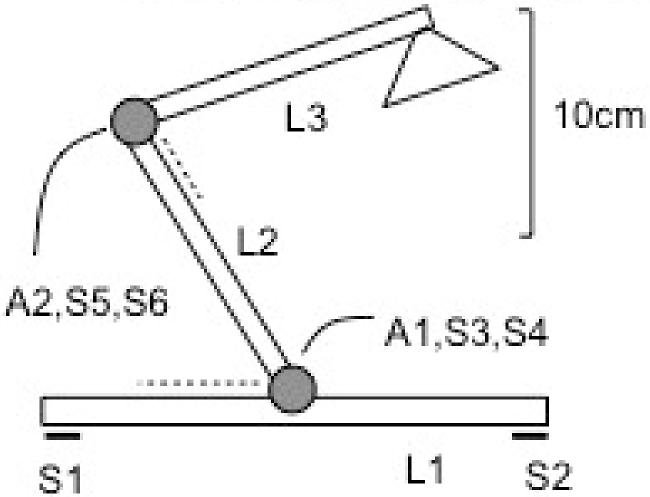


FIGURE 13. The bounder creature climbing a hill

mechanical configuration:



link	mass (kg)
L1	0.05
L2	0.10
L3	0.30

sensors:

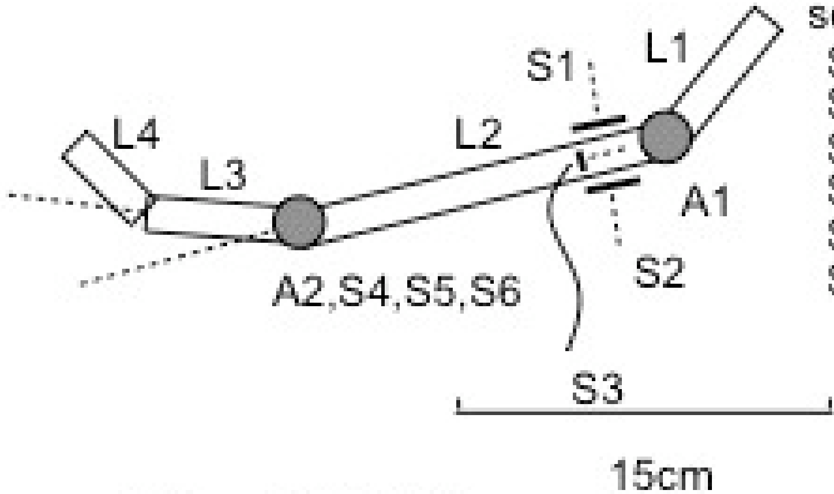
sensor	type	link	min	max
S1	touch	L1		
S2	touch	L1		
S3	angle	L2	−180	-70
S4	angle	L2	−53	180
S5	angle	L3	−100	75
S6	angle	L3	140	180

actuators:

act.	min	max	ks	kd
A1	−70	−50	0.05	0.001
A2	60	150	0.04	0.001

Luxo

mechanical configuration:



sensors:

sensor	type	link	min	max
S1	eye	L2	10	180
S2	eye	L2	−10	10
S3	eye	L2	−180	−10
S4	angle	L3	−180	−25
S5	angle	L3	−25	25
S6	angle	L3	25	180

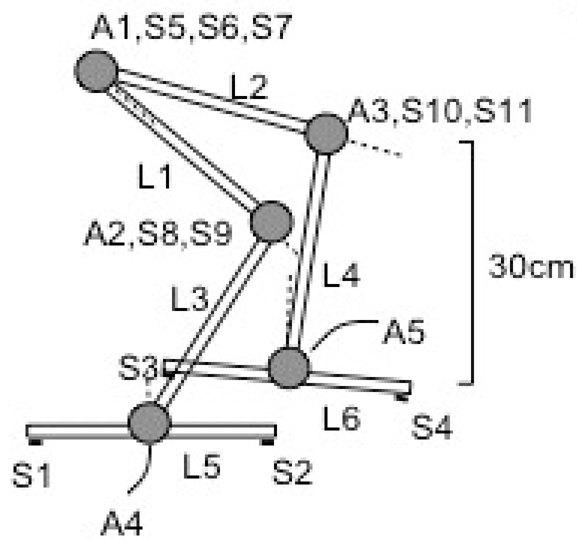
link	mass (kg)
L1	0.2
L2	1.0
L3	0.3
L4	0.1

actuators:

act.	min	max	ks	kd
A1	−20	20	0.003	0.001
A2	−40	40	0.006	0.001

The fish

mechanical configuration:



link	mass (kg)
L1	0.3
L2	0.3
L3	0.2
L4	0.2
L5	0.1
L6	0.1

sensors:

sensor	type	link	min	max
S1	touch	L5		
S2	touch	L5		
S3	touch	L6		
S4	touch	L6		
S5	angle	L2	−180	−15
S6	angle	L2	−15	−5
S7	angle	L2	15	180
S8	angle	L3	−180	−85
S9	angle	L3	−75	180
S10	angle	L4	−180	−85
S11	angle	L4	−75	180

actuators:

act.	min	max	ks	kd
A1	−30	30	0.15	0.01
A2	−105	−70	0.15	0.01
A3	−105	−70	0.15	0.01
A4	20	30	0.10	0.00[illegible]
A5	20	30	0.10	0.00[illegible]

The walker