Infants and iCubs: applying developmental psychology to robot shaping

James Law, Mark Lee, Martin Hülse, Patricia Shaw
Intelligent Robotics Group, Department of Computer Science, Aberystwyth University, Ceredigion, SY23 3DB, UK

Introduction

Despite the abundance of autonomous system in the natural world we have not managed to even approximate the competences and skills seen in humans and animals. One key reason is that robots, like humans but unlike other computational systems, are embedded in the real world and have to experience noisy, chaotic, unstructured environments. Even for robots with limited sensing and actuating capabilities the complexity arising from interactions with the real world makes unconstrained learning unreliable and computationally demanding.

Infants use scaffolding, or shaping, to overcome this sensory overload. Scaffolding, which can be produced by internal or external influences, guides the development of the infant to learn complex abilities from primitive beginnings through a sequence of staged development [1]. At each stage the infant is restricted by a series of constraints, which limit interaction and reduce the perceived complexity of the environment [2]. These constraints are eased over time as the infant learns to master its abilities, leading to further exploration and learning. We are using these ideas to create robots that learn developmentally.

Development in infancy

Our work is based on a thorough review of the neurological and psychological literature on infant development. The findings have been summarised in a timeline, part of which is shown below, describing the milestones in infant development from conception to 12 months postnatal. Our work is currently focused on understanding the development of sensorimotor competency, which is reflected in the chart.

	Age post-natal (months)						
	0 (At birth)	1	2	3	4	5	6
Neck	Rotation when supported, but insufficient torque otherwise.	General neck movements. Enough torque for short durations.	Sufficient torque to support head, general movements. Can lift to 45 degrees.	Good head control. Increasing mid-line orientation.			
	Increase in torque and position control						
Arms		Large, jerky movements.		Reach and miss. Smoother and more continuous movements. Two arm reaching.	Upper arms can support upper body. Increased disassociation with lower body.	Increased facility in forward reaching.	Extended arms can support upper body. Well directed reaching.
		Increase in shoulder torque					
					Increase in elbow torque		
		Increase in position control					
Hands		Closed hands at rest. Fingers fan when extending arms.	Hands mainly flexed. Involuntary object release.	Hands loosely open. Can open and close hands at will. Ulnar grasp.		Grasps objects in front of face with palmar grasp.	Radial-palmar grasp. Independent hand use.
		Increased parallel finger movement and control					
					Increase in individual finger use and control		
Torso			Torso movements.	Partial torso control. Sufficient torque and control to lift upper torso with arm support.		Rotation in upper trunk.	
			Increase in torque				
					Increase in position control		
Legs	Stepping reflex.	Large, jerky movement of legs. Fewer than in arms.		Large leg movements. Insufficient torque to support body.	Increased disassociation with upper body.	Foot to mouth.	Alternating leg movements. Almost sufficient torque in legs to support standing, insufficient balance. Sufficient control to leg-grasp objects.
		Increase in torque and position control					
Eyes	Move eyes toward diffuse light.	Turn head and eyes toward light source. Stares at light colours. Attracted to novel stimulus 6-10 inches from face. Basic object tracking. Few, jerky saccades, fixating on object edges.	More, smooth saccades. Ability to fixate within objects.	Gazes at human face. Visual exploration by moving head and eyes. Hand regard. Vergence control.	Smooth tracking.	Fixates on self.	Foot regard. Visual exploration by moving head and eyes. Attracted to novel visual stimulus. Eyes move in unison. Watches falling objects to resting place. Refinement of all eye movements.
	Improved eyeball position control						
Vision	Diffuse image, relatively sluggish image transfer rate. Lack of clarity in centre of visual field. Low sensitivity to stimulus.	Focus within limited range, around 21cm. Nonconjugate vision. Increase in field of view from 20 degrees at week 6 to 40 degrees at week 10.	Increased depth of focus. Increase in image resolution.	Higher quality image resolution, fast image transfer. Coarse stereopsis emerges. Colour vision similar to adults.			Increased sensitivity to stimuli. Increased resolution.
	Increase in resolution						
				Stereopsis onset and improvement			
	Increased sensitivity to stimulus						
	Increased colour resolution						
	Increased image transfer rate						
		Increase in field of view					
		Increase in focal range					
Hearing	Listens intently to quiet prolonged sounds. Can identify general direction of nearby sound source.						Can identify sound source location at 1.5 feet, except in midline.
	Increased ability to identify sound source location						
Additional observations	Freezes in response to quiet prolonged sounds. Close eyelids in response to sudden bright light. Fingers close in response to touch. Symmetric startle reflex to loud noise.	Turn head and eyes toward light or sound source. Fingers fan when extending arms.	Infants appear to show very little head movements during gaze shifts up to 30 degrees amplitude due to lack of strength in the neck muscles.	Visual exploration by moving head and eyes. 180 degree tracking with head and eyes. Infants make head movements about 25% of the time for 10 degree gaze shifts and all of the time for 30 degree gaze shifts. Between 11 and 28 weeks infants show an increase in the number of head movements made during combined eye-head smooth pursuit.		Can sit on lap and grasp objects.	Can grasp dangling objects. Foot grasp. Palmar grasp. Passes objects from hand to hand. Predominant 2-handed grasp.

Robot development

A developmental sequence for the iCub robot, that reflects that of the infant, can be drawn up by mapping the prototype infant example onto the available modalities and subsystems of the robot. We have performed such a mapping and produced a comprehensive chart of the general developmental possibilities for the sensory-motor systems of the iCub. The chart below is one portion of the iCub development chart, showing the development of motor ability from birth to month 10.

Motor system		Simulated age (months): "Birth" 1 2 3 4 5 6 7 8 9 10
Eyes	Pan, tilt	Increasing control
	Vergence	Increasing vergence
	Eyelids	Working
Neck	Roll, pitch, yaw	Increasing control
	Torque	Increasing torque
Shoulder	Roll, pitch, yaw	Increasing control
	Torque	Increasing torque
Elbow	Pitch	Increasing control
	Torque	Increasing torque
Wrist	Roll, pitch, yaw	Increasing control
Hand	Thumb opposition	Increasing range of opposition
	Thumb	Thumb refinement
	Fingers	Parallel finger use; Individual finger refinement
	Grasps	Ulnar; Palmar; Radial; Pincer
Torso	roll	
	pitch	Increasing movement precision
	yaw	Increasing movement precision
	torque	Increasing torque

Constraints

We believe the gradual learning of sensory and motor skills is achieved through the modulating influence of a dynamic constraint network, following our approach towards constraint based learning [3]. Constraints can be imposed by cognitive, sensorimotor, anatomical and hardware properties of the agent, as well as general maturational limitations and environmental effects. We construct a set of possible constraint tables that show the relationships between different constraints and when they are relevant in the developmental sequence.

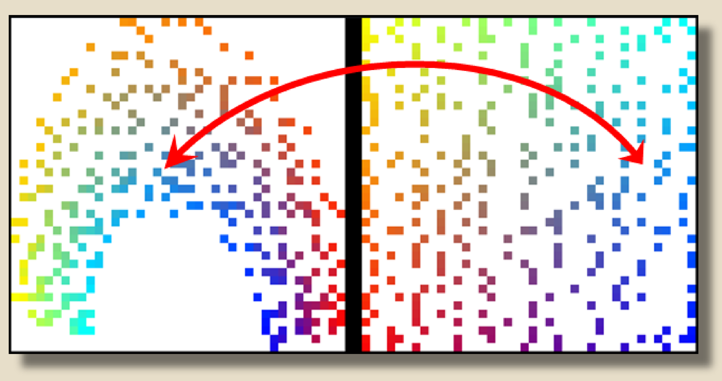
Developmental stage	"Age" (months)	Shoulder pitch	Shoulder roll	Shoulder yaw	Shoulder torque	Elbow pitch	Elbow torque	Wrist roll	Wrist pitch	Wrist yaw	Torso roll	Torso pitch	Torso yaw	Torso torque	Saturation criteria	Observed behaviour
1 Shoulder movements	2	d	d	d	d										Low occurence of unknown movements	Arm moves in all directions from shoulder
2 Elbow movements	2					d									Low occurence of unknown movements	Onset of elbow movement
3 Shoulder and elbow movements	2	d	d	d	d	d									Low occurance of unknown combinations of movements	Weak, unrefined, combined shoulder and elbow movements
4 Torso pitch	2											d		d	Low occurence of unknown movements	Torso bends foraward and backward
5 Reaching while bending	2	d	d	d	d	d						d		d	Low occurance of unknown combinations of movements	Reaching while bending at waist
6 Torso pitch and yaw	3											d	d	d	Low occurence of unknown movements	Torso bends forwards, backwards and sideways at waist
7 Reaching with torso pitch and yaw	3	d	d	d	d	d						d	d	d	Low occurance of unknown combinations of movements	Reaching while bending and leaning from waist
8 Improved torso torque	4	d	d	d	d	d	d					d	d	x	Low occurence of unknown movements	Stronger movements in elbow and waist
9 Torso roll, pitch and yaw	5										x	d	d	x	Low occurence of unknown movements	Torso bends, leans and rotates at waist
10 Reaching with torso movement	5	d	d	d	x	d	d				x	d	d	x	Low occurance of unknown combinations of movements	Reaching whilst bending, leaning and turning
11 Wrist movement	6							d	d	d					Low occurence of unknown movements	Onset of wrist movement
12 Whole arm reach with body movement	6	d	d	d	x	d	d	d	d	d	x	d	d	x	Low occurance of unknown combinations of movements	Unrefined full arm manipulation
13 Arm refinement	7	x	x	x	x	x	x	d	d	d	x	x	d	x	Few improvements in elbow and shoulder movements	Refined full arm manipulation
14 Developed torso yaw	10	x	x	x	x	x	x	d	d	d	x	x	x	x	Few improvements in torso yaw	Refined torso yaw
15 Complete reach	11	x	x	x	x	x	x	x	x	x	x	x	x	x	Few improvements in wrist movements	Fully developed reaching

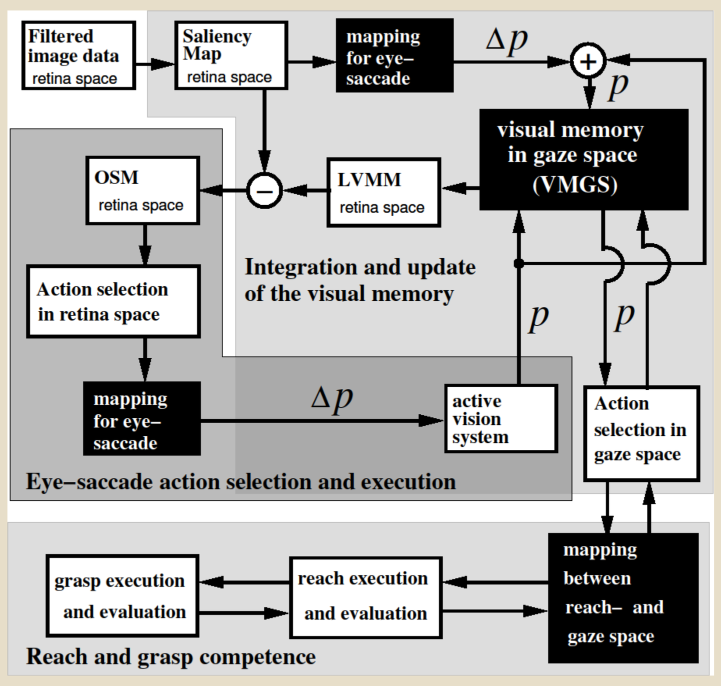
At each stage in development, constraints are in place restricting the system to a limited number of functions. Stages have an associated saturation criterion that, when met, triggers a change in the constraints imposed on the system. This may be an easing of constraints on a particular function, or a complete removal of a constraint. The stages indicated in these constraints systems are not fixed in their order, nor are they triggered in isolation. Instead, stage transitions are emergent: their ordering and timing are not easily predictable, being subject to the requirements and activities of the robot. Indeed, the system may even regress to earlier stages when an action cannot be successfully learned due to gaps in the system's previous experience. For this reason any implementation may be expected to show noticeable local variations although the system as a whole will follow the general timeline for infant development.

A framework for cognition

Our constraint based framework provides a basis for exploring robot cognition. We are investigating *motor babbling* and *intrinsic motivation* as mechanisms for driving the developmental stages, and *visual salience* and *affordance learning* for environmental interaction. This is leading us to future work on:

- Coordination learning
- Multimodal transfer
- Multimodal sensing
- External shaping
- Stage emergence and sensitive periods





Summary

While developmental robotics research often refers to the findings of Piaget and others, and sometimes acknowledges the cephalocaudal flow of development, we propose that knowledge of the finer patterns of development and the associated constraints will provide a richer understanding of robot shaping that will have wide applicability to robotics research. In the longer term, we believe such methods will mature into general principles for various humanoid robot designs, as the approach does not prescribe the very detailed level of sensorimotor properties but allows the system to discover these. Hence such developmental architectures should have wide applicability. We also hope the models produced will have some insight value for cognitive science.

References

[1] J. Bruner. Acts of Meaning. Harvard University Press, Cambridge, MA, 1990.
[2] J. Rutkowska. Scaling up sensorimotor systems: Constraints from human infancy. Adaptive Behaviour, 2:349-373, 1994.
[3] M. Lee, Q. Meng, and F. Chao. Staged competence learning in developmental robotics. Adaptive Behaviour, 15(3):241-255, 2007.

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