Energy Efficient Execution of POMDP Policies

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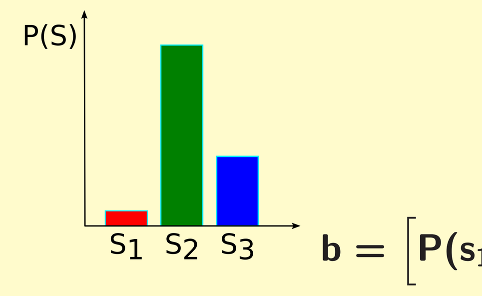
Motivation and Contribution

- Moving towards the "Internet of Things", we could envision having POMDPs installed on all kinds of devices, including the smallest ones
- We performed real tests that showed that finite-state controllers (FSCs) are the most energy efficient POMDP policies
- Efficient and robust algorithms that compute small policies/controllers become desirable
- Here, we show how various kinds of POMDP policies can be compiled into finite-state controllers

POMDP

Partially Observable Markov Decision Process

- an elegant framework for planning under uncertainty
- allows for uncertainty about transitions, sensors, and the state of the world



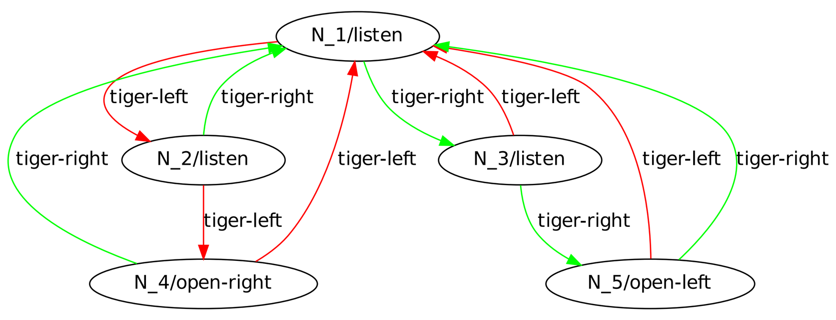
$b = \left[P(s_1), P(s_2), P(s_3)\right]$

$$\begin{bmatrix}\alpha_1(s_1)\\ \alpha_1(s_2)\\ \alpha_1(s_3)\end{bmatrix}, \begin{bmatrix}\alpha_2(s_1)\\ \alpha_2(s_2)\\ \alpha_2(s_3)\end{bmatrix}, \ldots, \begin{bmatrix}\alpha_N(s_1)\\ \alpha_N(s_2)\\ \alpha_N(s_3)\end{bmatrix}$$

a_1 a_2 $\ldots$ a_N

Policy Execution: α-vectors vs. Finite-state Controllers

b $\leftarrow$ an initial belief
while (true)
  action $\leftarrow$ determine an action for b using alpha vectors
  execute the action
  read observations from sensors
  update b using observations and the action
end



No need to do a belief update nor to consult alpha-vectors.

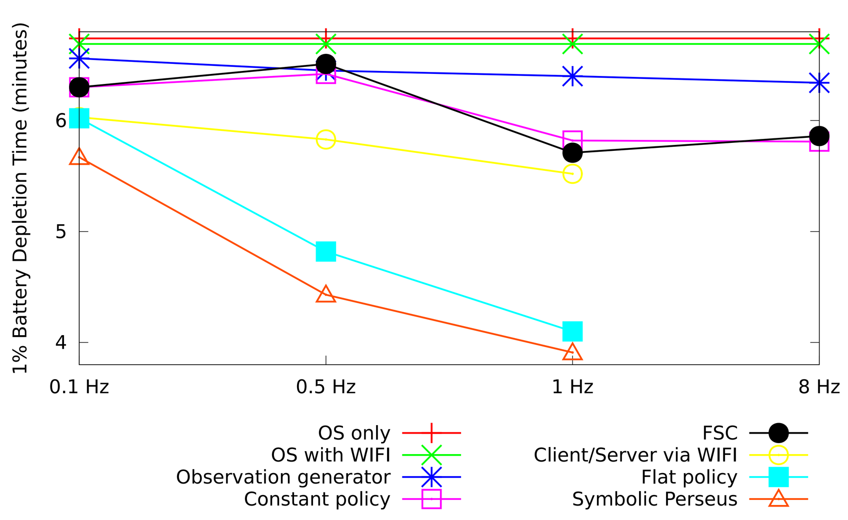
Battery Efficiency Experiment

- A POMDP, lacasa4.batt, with 2880 states, 72 observations, and 6 actions (designed and generated using WEB-SNAP, see Grzes *et al.* IJAR 2014)
- Installed on a smart phone to assist a cognitively disabled person; allows the patient to enjoy her walk, helps find way home when lost, or calls a care giver when necessary
- When the patient is lost and the phone runs out of battery, the application is not available
- Relying on cloud computing requires a reliable network connection and server infrastructure

Battery Efficiency on the Nexus 4 Phone

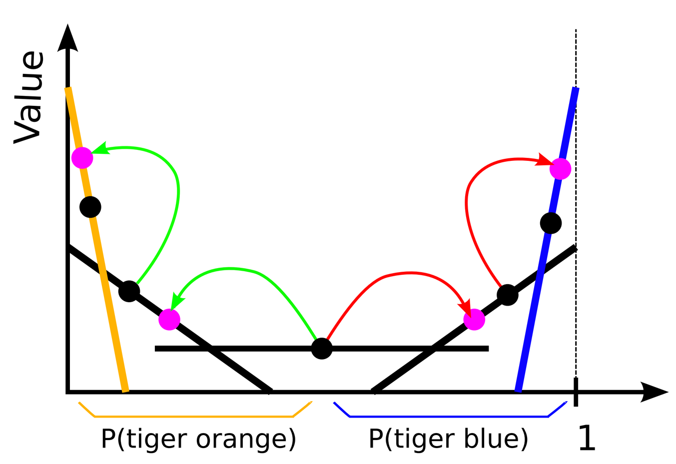
Experiment	1% battery depletion time (minutes)	standard error
OS only	6.74	0.13
OS with WIFI	6.69	0.08
Observation generator	6.40	0.26
Constant policy	5.82	0.21
FSC	5.71	0.18
Client/Server (cloud)	5.52	0.22
Flat policy	4.10	0.11
Symbolic Perseus	3.91	0.15

Policies for lacasa4.batt evaluated on the Nexus 4 phone. Every policy was queried once per second (time interval 1 second).

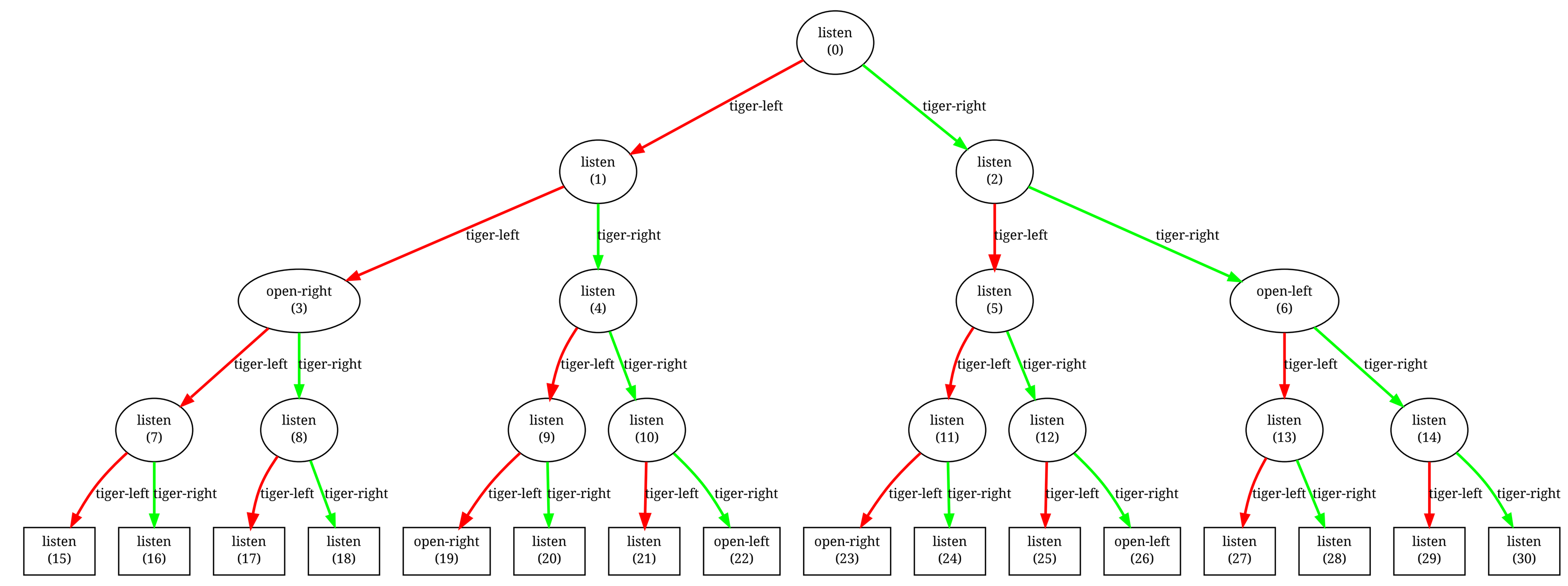


Battery consumption results on the Nexus 4 phone. Missing values indicate that the policy did not return fast enough for a given frequency.

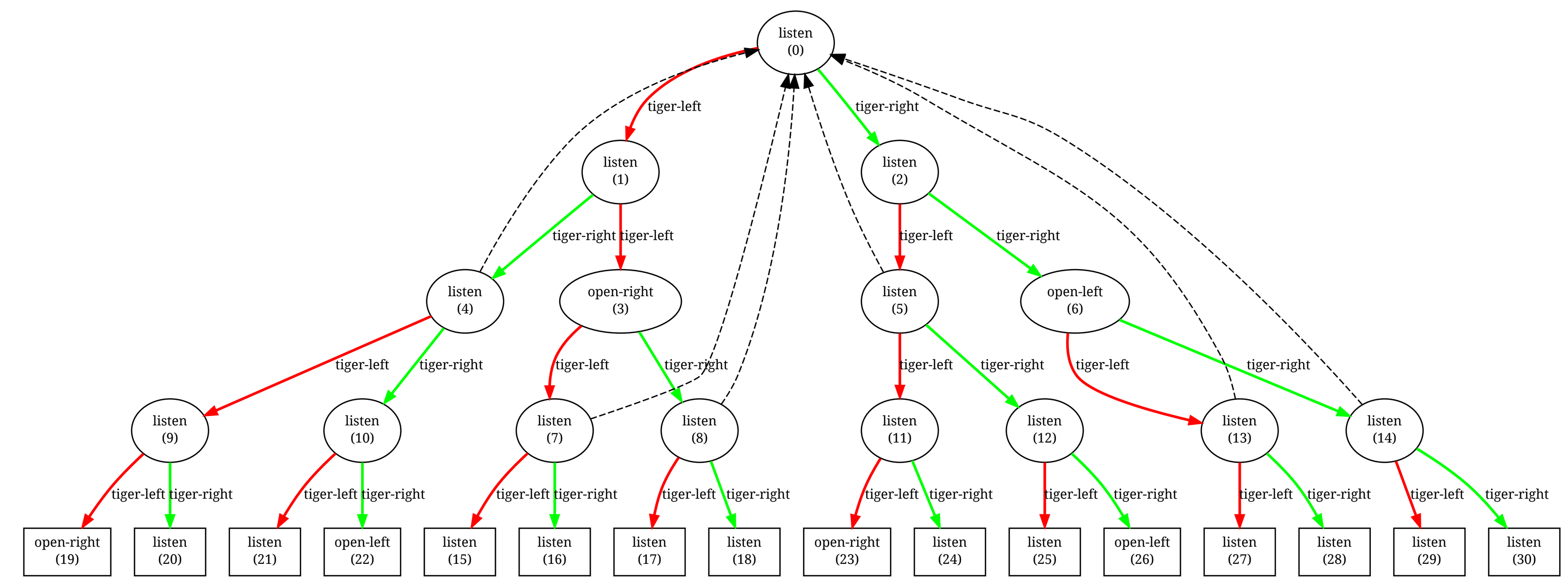
Controller Compilation Using α-vectors



Controller Compilation Using Policy Trees: (1) Policy Tree



Controller Compilation Using Policy Trees: (2) Identical Conditional Plans



Controller Compilation: Pruning

Controller Compilation Results

POMDP	GapMin	method	depth	tree size	nodes	value	time	c
chainOfChains3	GM-lb=157	**alpha2fsc**	10	10	10(10)	**157**(157)	0.26	0
$\lvert\mathbf{S}\rvert$=10, $\lvert\mathbf{A}\rvert$=4	GM-ub=157	**GM-LB**	11	11	10(10)	**157**(157)	0.42	0
$\lvert\mathbf{O}\rvert$=1, $\gamma = \mathbf{0.95}$	time=0.86s	**GM-UB**	11	11	10(10)	**157**(157)	0.26	0
	$\lvert\mathbf{lb}\rvert$=10	**B&B**			10	**157**	1.69	
	$\lvert\mathbf{ub}\rvert$=1	EM			10	0.17 ± 0.06	6.9	
		QCLP			10	0 ± 0	0.16	
		BPI			10	25.7 ± 0.77	4.25	
cheese-taxi	GM-lb=2.481	**alpha2fsc**			17(22)	**2.476**(2.476)	0.29	1
$\lvert\mathbf{S}\rvert$=34, $\lvert\mathbf{A}\rvert$=7	GM-ub=2.481	**GM-LB**	15	167	17(24)	**2.476**(2.476)	0.56	1
$\lvert\mathbf{O}\rvert$=10, $\gamma = \mathbf{0.95}$	time=1.88s	**GM-UB**	15	167	17(24)	**2.476**(2.476)	0.55	1
	$\lvert\mathbf{lb}\rvert$=22	B&B			10	-19.9*	24h	
	$\lvert\mathbf{ub}\rvert$=13	EM			17	-12.16 ± 2.08	337.9	
		QCLP			17	-18.22 ± 1.77	227.4	
		BPI			16	-18.1 ± 0.39	7.18	
lacasa4.batt	GM-lb=291.1	alpha2fsc			10(10)	285.5(285.5)	302	0
$\lvert\mathbf{S}\rvert$=2880, $\lvert\mathbf{A}\rvert$=6	GM-ub=292.6	GM-LB	3	745	19(22)	287.3(287.1)	3652	1
$\lvert\mathbf{O}\rvert$=72, $\gamma = \mathbf{0.95}$	time=8454s	**GM-UB**	4	23209	87(94)	**290.8**(290.8)	3681	1
	$\lvert\mathbf{lb}\rvert$=10	B&B			10	285.0*	24h	
	$\lvert\mathbf{ub}\rvert$=23	EM			3	290.2 ± 0.0	19920	
		BPI			6	290.6 ± 0.2	4124	
machine	GM-lb=62.38	alpha2fsc			5(39)	54.61(54.09)	5.53	1
$\lvert\mathbf{S}\rvert$=256, $\lvert\mathbf{A}\rvert$=4	GM-ub=66.32	GM-LB	9	376	26(41)	62.92(62.84)	18.5	1
$\lvert\mathbf{O}\rvert$=16, $\gamma = \mathbf{0.99}$	time=3784s	**GM-UB**	12	2864	11(159)	**63.02**(60.29)	86.8	2
	$\lvert\mathbf{lb}\rvert$=39	B&B			6	62.6	52100	
	$\lvert\mathbf{ub}\rvert$=243	EM			11	62.93 ± 0.03	1757	
		QCLP			11	62.45 ± 0.22	4636	
		BPI			10	35.7 ± 0.52	2.14	

Table 1 : Selected Compilations of GapMin Policies

POMDP	SARSOP	method	depth	tree size	nodes	value	time	c
baseball	time 122.7s	**policy2fsc**	7	175985	10(47)	**0.641**(0.641)	78.22	1
$\lvert\mathbf{S}\rvert$=7681, $\lvert\mathbf{A}\rvert$=6	$\lvert\alpha\rvert$ =1415	B&B			5	0.636*	24h	
$\lvert\mathbf{O}\rvert$=9, $\gamma = \mathbf{0.999}$	UB=0.642	EM			2	0.636 ± 0.0	48656	
	LB=0.641	BPI			9	0.636 ± 0.0	445	
elevators_inst_pomdp_1	time 11,228s	**policy2fsc**	11	419	20(24)	**-44.41**(-44.41)	1357	1
$\lvert\mathbf{S}\rvert$=8192, $\lvert\mathbf{A}\rvert$=5	$\lvert\alpha\rvert$ =78035	B&B			10	-149.0*	24h	
$\lvert\mathbf{O}\rvert$=32, $\gamma = \mathbf{0.99}$	UB=-44.31							
	LB=-44.32							
tagAvoid	time 10,073s	**policy2fsc**	28	7678	91(712)	**-6.04**(-6.04)	582.2	1
$\lvert\mathbf{S}\rvert$=870, $\lvert\mathbf{A}\rvert$=5	$\lvert\alpha\rvert$ =20326	B&B			10	-19.9*	24h	
$\lvert\mathbf{O}\rvert$=30, $\gamma = \mathbf{0.95}$	UB=-3.42	EM			9	-6.81 ± 0.12	19295	
	LB=-6.09	QCLP			2	-19.99 ± 0.0	12.9	
		BPI			88	-12.42 ± 0.13	1808	
underwaterNav	time 10,222s	policy2fsc	51	1242	52(146)	745.3(745.3)	5308	1
$\lvert\mathbf{S}\rvert$=2653, $\lvert\mathbf{A}\rvert$=6	$\lvert\alpha\rvert$ =26331	B&B			10	747.0*	24h	
$\lvert\mathbf{O}\rvert$=103, $\gamma = \mathbf{0.95}$	UB=753.8	**EM**			5	**749.9** ± 0.02	31611	
	LB=742.7	BPI			49	748.6 ± 0.24	14758	
rockSample-7_8	time 10,629s	**policy2fsc**	31	2237	204(224)	**21.58**(21.58)	1291	1
$\lvert\mathbf{S}\rvert$=12545, $\lvert\mathbf{A}\rvert$=13	$\lvert\alpha\rvert$ =12561	B&B			10	11.9*	24h	
$\lvert\mathbf{O}\rvert$=2, $\gamma = \mathbf{0.95}$	UB=24.22	BPI			5	7.35 ± 0.0	78.8	
	LB=21.50							

Table 2 : Compilation and compression of SARSOP policies.

Conclusion

- Energy consumption can limit deployment of POMDPs on mobile devices
- We demonstrated that finite-state controllers are the cheapest POMDP policies to execute
- Two methods to compile POMDP policies into finite-state controllers were shown
- Compilation is more robust against local optima than direct optimization with local search
- Compilation is feasible on large problems where exhaustive search with branch-and-bound can be challenging
- More time spent during off-line POMDP planning may lead to huge battery/energy savings when the policy is deployed on thousands of mobile phones
- For recent advancements on direct optimisation see Grzes & Poupart AAMAS 2015

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