Improving the Quality of Supervised Finite-State Machine Construction Using Real-Valued Variables

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Introduction

We focus on finite-state machines (FSMs) for control tasks.

Why FSMs?

- Easy to comprehend and visualize
- Can be formally verified with the *Model Checking* approach

Where FSMs can be applied?

- Control systems: for energy, aircraft, space industries...
- Where reliability is important

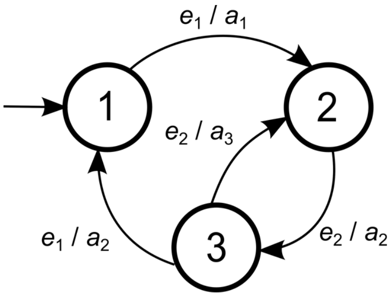
FSMs now:

- Quantum Leaps
- IEC 61499 standard for distributed PLC systems
- StateFlow for MATLAB

FSM: definition

$\text{FSM} = (S, s_0, E, A, \delta, \lambda)$

- S – finite set of states
- s_0 – initial state
- E – event set
- A – action set
- $\delta : S \times E \to S$ – transition function
- $\lambda : S \times E \to A$ – output function



Inducing FSMs from specification

Specification:

- Tests / scenarios, software traces
- Temporal properties (LTL, CTL formulae)
  - Example: $\mathsf{G}\,((p \land \neg q) \rightarrow \mathsf{X}\,r)$

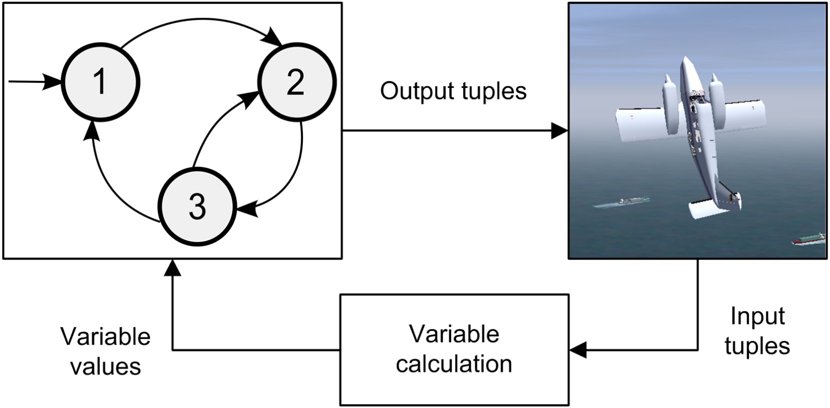
FSMs:

- Are software models
- Can be induced with metaheuristics (see Tsarev & Egorov, GECCO '11)
- Can be easily transformed into source code

Considered problem in brief

- Induce an FSM to control an object in a complex environment with **continuous** inputs and outputs
- $\text{in}[i, t]$, $\text{out}[i, t]$ – training data ($i = 1..N$ is a number of a test, $t = 1..\text{len}[i]$ is a timestamp)
- The **aircraft control** problem is considered as an example (*FlightGear* simulator is used)
- Inputs correspond to sensor values, outputs correspond to control device positions
- Methodology:

FSM and aircraft interaction

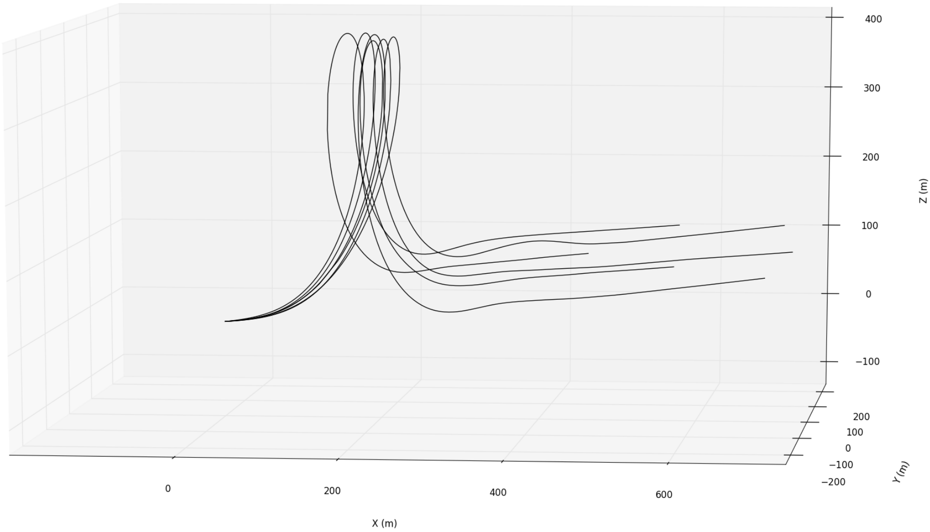


Test example

Values	Description	$t = 1$	...	$t = 10$	...
$\text{in}[i, t]_1$	Pitch angle (°)	3.078	...	3.544	...
$\text{in}[i, t]_2$	Roll angle (°)	-0.076	...	0.351	...
$\text{in}[i, t]_3$	Heading (°)	198.03	...	198.11	...
$\text{in}[i, t]_4$	Airspeed (knots)	251.42	...	252.29	...
$\text{out}[i, t]_1$	Aileron position	0.000	...	0.032	...
$\text{out}[i, t]_2$	Rudder position	0.000	...	0.016	...
$\text{out}[i, t]_3$	Elevator position	-0.035	...	-0.039	...

Test example (4 inputs, 3 outputs)

Aircraft path examples (loop)



Previous works

- A. Alexandrov, A. Sergushichev, S. Kazakov, F. Tsarev. Genetic algorithm for induction of finite automata with continuous and discrete output actions. GECCO '11 Companion, pp. 775–778. ACM, 2011.
  - GA, several hours to construct an FSM
  - Inputs are transformed to **predicate** values
  - Several transitions per time step (for each predicate)
  - Automatic output derivation
- I. Buzhinsky, V. Ulyantsev, A. Shalyto. Test-based induction of finite-state machines with continuous output actions. Proceedings of MIM '13, pp. 1049–1054. IFAC, 2013.
  - ACO, about 10 minutes to construct an FSM

Proposed approach (outline)

Predicates for transitions:

- Example: $p(\text{input}) = (\text{input}_2 < 3.6)$
- One transition per time step
- Only few ("significant") predicates are used in each state
- Example of a transition table:

Condition	$\neg p_1 \wedge p_3$	$\neg p_1 \wedge p_3$	$p_1 \wedge \neg p_3$	$p_1 \wedge p_3$
New state	2	4	1	1

Real-valued **variables** for output actions:

- Example: $v(\text{input}) = (\text{input}_1 - 0.5)^2$
- Action update: $u'_i = u_i + \sum_{i=1}^{k} r_{s,i,j}\, v_i$, where $r_{s,i,j}$ are constant for a fixed FSM

Individual

- Initial state

For each state:

- Mask of predicate significance
- Transition table for all combinations of values of significant predicates
- Mask of variable significance for each control device (output)

Actions (values $r_{s,i,j}$) **are not included in individuals, but are derived** using a procedure which reminds solving normal equation for linear regression. Linearity of the action update is important here.

FSM example (one state)

Upper box: included in an individual

Predicate significance mask			
p_1	p_2	p_3	p_4
✓	✗	✓	✗

Transition table (from the current state)			
$\neg p_1 \wedge \neg p_3$	$\neg p_1 \wedge p_3$	$p_1 \wedge \neg p_3$	$p_1 \wedge p_3$
2	4	1	1

Variable significance mask for output 1			
$v_{1,1}$	$v_{1,2}$	$v_{1,3}$	$v_{1,4}$
✗	✓	✗	✓

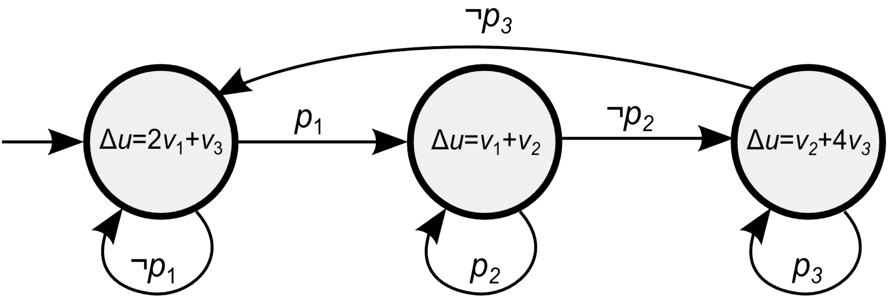
Variable significance mask for output 2				
$v_{2,1}$	$v_{2,2}$	$v_{2,3}$	$v_{2,4}$	$v_{2,5}$
✓	✗	✗	✗	✓

Output action 1			
$r_{s,1,1}$	$r_{s,2,1}$	$r_{s,3,1}$	$r_{s,4,1}$
0	**1.2**	0	**0.3**
$\Delta u_1 = \mathbf{1.2}\, v_{1,2} + \mathbf{0.3}\, v_{1,4}$			

Output action 2				
$r_{s,1,2}$	$r_{s,2,2}$	$r_{s,3,2}$	$r_{s,4,2}$	$r_{s,5,2}$
3.7	0	0	0	**−0.3**
$\Delta u_2 = \mathbf{3.7}\, v_{2,1} - \mathbf{0.3}\, v_{2,5}$				

Lower box: derived for each individual

FSM example (transition graph)



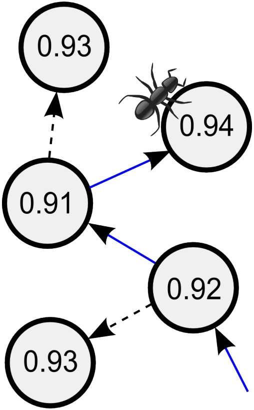
- Example for 3 predicates, 3 variables, and one output u
- Similar masks and actions in each state

Fitness function

- Fitness function: $f = 1 - P_\rho - P_\tau$
- P_ρ: penalty for the distances between the reference outputs (out$[i, t]$) and the outputs produced by the individual, executed on tests
- P_τ: penalty for **state changes** (an FSM with clearly distinct states is better)
- f is maximized for each individual

Search optimization

- ACO-based algorithm
- D. Chivilikhin, V. Ulyantsev.
  MuACOsm – a new mutation-based ant colony optimization algorithm for learning finite-state machines.
  Proceedings of GECCO '13,
  pp. 511–518. ACM, 2013.
- Uses only mutations
- Simplification: pheromone removed
- Parameters were tuned with *irace*



Experimental setup

- Proposed FSM representation (induced with the modified fitness function) vs. Alexandrov et al.
- 50 ACO executions for each combination of the FSM representation, number of states $|S| = 3, 4, 5$ and test set (loop, barrel roll, turn)
- Termination criterion: stagnation after 5000 fitness evaluations
- About 10 minutes for each execution on a quad-core computer

- Individual with maximum value of f for each execution was run in simulation 10 times
- Roll and pitch quality metrics were compared across the representations

Results: fitness values

$\|S\|$	FSM Representation	Loop	Barrel roll	Turn
3	Proposed	**0.9856**	**0.9854**	0.9892
	Previous	0.9812	0.9832	0.9894
4	Proposed	**0.9866**	**0.9863**	0.9898
	Previous	0.9836	0.9856	0.9901
5	Proposed	**0.9873**	**0.9868**	0.9901
	Previous	0.9842	0.9858	0.9902

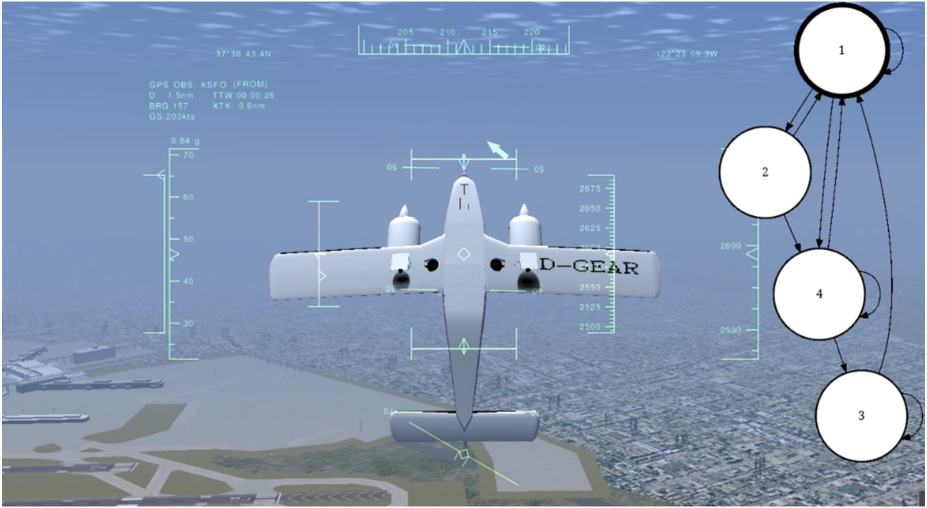
Median fitness values for different test sets and number of states

Results: simulation

$|S|$	FSM Representation	Loop	Barrel roll	Turn
3	Proposed	**1.71/17.21**	**16.52/3.20**	**4.80/1.95**
	Previous	6.37/20.54	18.56/4.44	50.29/7.58
4	Proposed	2.41/23.04	**15.35/2.51**	**4.10/1.42**
	Previous	6.32/22.11	21.86/4.08	57.04/6.79
5	Proposed	3.21/25.27	**14.74/2.43**	**4.07/1.36**
	Previous	9.54/24.44	22.99/4.68	45.83/7.83

Median roll/pitch errors ($^\circ$) for different test sets and number of states

A screenshot (loop, FlightGear simulator)



A screenshot (180° turn, FlightGear simulator)

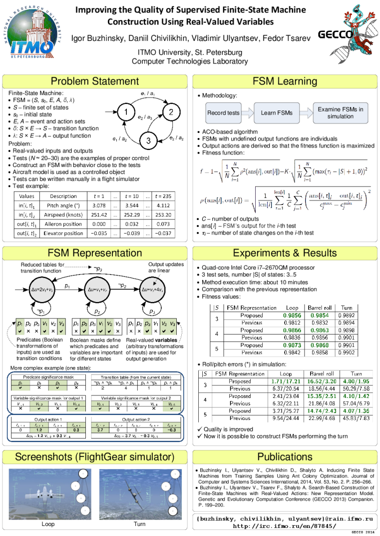
Conclusion

- A new representation method for FSMs with continuous inputs and outputs
- Automatic output derivation for the new representation
- A known fitness function was modified to get more comprehensible FSMs
- Simulation quality of FSMs was improved

Future work

- Automatic construction of predicates and variables
- Testing the approach in different environments (e.g. robot simulators)
- Involving more types of specification (including temporal properties)

Our posters



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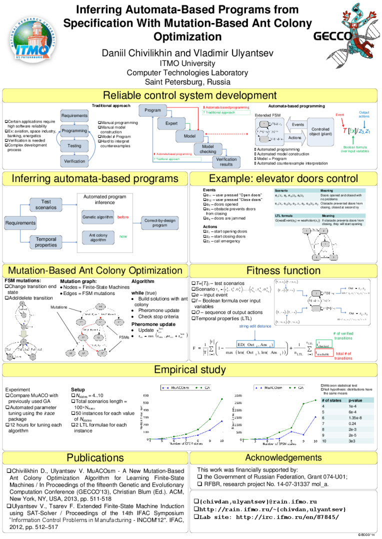
Problem Statement
FSM Learning
Record tests
Learn FSMs
Examine FSMs in simulation
FSM Representation
Experiments & Results
Screenshots (FlightGear simulator)
Loop
Turn
Publications



Inferring Automata-Based Programs from Specification With Mutation-Based Ant Colony Optimization
Daniil Chivilikhin and Vladimir Ulyantsev
ITMO University
Computer Technologies Laboratory
Saint Petersburg, Russia
GECCO
Reliable control system development
Inferring automata-based programs
Example: elevator doors control
Mutation-Based Ant Colony Optimization
Fitness function
Empirical study
Publications
Acknowledgements

Thank you for your attention!
Any questions?

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