

Supplementary Material

Table 1: Detailed validation results of THEMIS⁺'s clues on the missed bugs w.r.t. the clues manually found by developers.

Bugs	W	F	A	C	St	D	H
AD-118	◇	◇	✓	◇		◇	✓
AD-285		✓	✓	✓	✓	✓	✓
AFM-1232	✓	✓	✓	◇		✓	✓
AFM-1796							✓
AFM-1837	✓	✓	✓	✓	✓	✓	✓
AB-261	✓		✓	✓	✓	✓	✓
AB-375	◇		✓	✓	✓	✓	✓
AB-480					✓	✓	✓
AB-697	✓	✓	✓	✓	◇	◇	✓
AB-703	◇	✓	✓	✓	✓	◇	◇
Anki-4200						✓	
Anki-4451		✓	✓	◇	✓		
Anki-4707							
Anki-4977							
Anki-5638	◇	◇	◇	◇	◇	◇	◇
Anki-5756							
Anki-6145	✓	✓	✓	✓	✓	✓	✓
APM-116							
collect-3222							◇
comm-1385		◇		✓	◇	◇	◇
comm-1391	◇	✓	✓	◇	◇	✓	✓
comm-1581	◇		◇	◇	◇	◇	◇
comm-2123						✓	
comm-3244	✓	◇	◇	◇	✓		
FL-#4881	✓	◇	✓	✓	✓	✓	✓
FL-#4942				✓			
FL-#5085					✓		✓
GHD-#73							
MFB-#224	◇		◇		◇	◇	◇
NC-#1918		✓		✓	✓		
NC-#4026						✓	
NC-#4792	✓	✓		✓	✓	✓	✓
NC-#5173							
ON-#745	✓		◇	✓			
OEAA-#2198							
OL-#67	✓				◇	◇	◇
OE4A-#637	✓	✓	◇	✓	◇	◇	◇
OE4A-#729	✓				✓	◇	✓
SN-#114	◇	✓	✓	◇	✓	✓	✓
SF-#239	◇	◇	◇	◇	◇	◇	◇
WP-#6530	✓	✓	✓	✓	✓	✓	◇
WP-#7182	◇	◇	◇	✓	◇	◇	◇
WP-#10302							
WP-#10363							
WP-#10547			✓				
WP-#11135							
WP-#11992					✓	◇	

1 SUPPLEMENTARY MATERIAL OF RQ2

Table 1 shows the detailed validation results of THEMIS⁺'s clues on the missed bugs, compared to the clues manually found by tool developers. Column "Bugs" denotes the 47 real-world bugs from THEMIS used in our study, and column "W", "F", "A", "C", "St", "D" and "H" denote the seven testing tools, *i.e.*, WCTESTER, FASTBOT, APE, COMBODROID, STOAT, DROIDBOT and HUMANOID, respectively. The symbol "✓" denotes that THEMIS⁺'s clues on the missed bug are *useful* w.r.t. the clues manually found by tool developers, while "◇" denotes that THEMIS⁺'s clues on the missed bug are *identical* w.r.t. the clues manually found by tool developers.

2 DETAILED RESULTS OF RQ3

The detailed results of RQ3 are shown in Table 2. Column "TC", "RV" and "AB" give the first missed event (in the form of event ID) in the bug-triggering trace reported by simple trace comparison (TC), simple runtime verification (RV) and our automata-based trace analysis approach (AB), respectively. Symbol "-" indicates the corresponding bug was found by the testing tool (and thus we do not need to analyze these cases). Symbol "/" denotes the analysis result is not available due to some tool issues. The cells in gray under Column "TC" or "RV" denote that the corresponding first missed events found by TC and RV are consistent with AB, respectively. The last row "#Correct" gives the numbers of missed bugs for which "TC", "RV" and "AB" give the *correct* clues in terms of the first missed event in the bug-triggering trace, respectively. Note that the results of AB are all correct according to RQ2.

Table 2: Detailed results of simple trace comparison (TC), simple runtime verification (RV) and our automata-based trace analysis approach (AB) in terms of the first missed event (in the form of event ID) in the bug-triggering trace.

Bugs	WCTESTER			FASTBOT			APE			COMBODROID			MONKEY			STOAT			DROIDBOT			HUMANOID			Q-TESTING		
	TC	RV	AB	TC	RV	AB	TC	RV	AB	TC	RV	AB	TC	RV	AB	TC	RV	AB	TC	RV	AB	TC	RV	AB	TC	RV	AB
AD-118	3	3	3	2	3	3	2	2	3	2	2	3	1	1	3	-	-	-	3	5	6	-	-	-	2	2	3
AD-285	-	-	-	2	3	4	2	3	4	3	3	6	2	2	4	2	3	4	2	3	4	1	1	4	-	-	-
AFM-1232	3	1	4	3	1	4	1	1	4	1	1	4	1	1	4	-	-	-	3	1	4	3	1	4	2	1	4
AFM-1796	-	-	-	-	-	-	-	-	-	-	-	-	1	3	3	-	-	-	-	-	-	3	1	3	-	-	-
AFM-1837	2	2	2	2	2	3	2	2	3	2	2	3	-	-	-	2	2	2	2	2	2	2	2	2	2	2	2
AB-261	2	2	3	-	-	-	3	1	5	3	1	3	3	1	4	3	1	3	2	3	3	3	1	7	2	1	3
AB-375	4	8	8	-	-	-	3	1	4	3	1	3	3	4	8	4	3	4	3	7	7	2	7	4	2	3	3
AB-480	3	2	5	4	2	5	3	2	c	4	2	5	3	5	5	4	4	6	2	5	5	3	2	5	2	2	5
AB-697	3	1	4	5	5	5	2	1	6	2	1	5	2	1	4	4	4	4	4	5	5	4	5	5	3	1	4
AB-703	3	1	4	4	4	4	4	1	4	4	1	4	2	1	4	4	4	4	4	4	4	4	4	4	3	1	4
Anki-4200	-	-	-	-	-	-	-	-	-	-	-	-	2	1	2	-	-	-	2	1	3	-	-	-	2	1	2
Anki-4451	-	-	-	2	4	6	2	4	7	3	7	7	2	4	6	2	7	7	-	-	-	-	-	-	/	/	/
Anki-4707	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	/	/	/
Anki-4977	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Anki-5638	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Anki-5756	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Anki-6145	2	4	7	2	4	6	2	1	6	2	5	7	2	4	7	2	5	6	4	5	6	2	2	6	2	5	6
APM-116	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
collect-3222	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	2	4	1	2	2
comm-1385	-	-	-	3	3	3	-	-	-	3	3	4	3	2	3	3	3	4	2	2	3	2	2	3	/	/	/
comm-1391	2	2	2	2	2	2	2	2	3	2	2	2	1	2	1	2	2	2	2	2	3	1	2	5	/	/	/
comm-1581	2	2	1	2	2	1	2	2	1	1	2	1	2	1	4	2	2	1	2	2	1	2	2	1	/	/	/
comm-2123	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4	4	4	-	-	-	/	/	/
comm-3244	3	3	5	3	3	5	3	4	5	1	1	1	2	3	4	3	3	3	-	-	-	/	/	/	/	/	/
FL-4881	2	2	2	2	2	3	2	2	2	2	2	2	1	1	3	2	2	2	2	2	2	1	1	2	1	1	1
FL-4942	-	-	-	-	-	-	-	-	-	1	1	4	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1
FL-5085	-	-	-	-	-	-	-	-	-	-	-	-	2	2	3	2	3	3	-	-	-	1	1	3	1	1	1
GHD-73	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
MFB-224	1	1	1	-	-	-	1	1	1	-	-	-	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
NC-1918	-	-	-	1	1	1	-	-	-	1	1	1	-	-	-	1	1	1	-	-	-	-	-	-	/	/	/
NC-4026	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	2	2	-	-	-	/	/	/
NC-4792	2	1	4	2	1	4	-	-	-	2	2	4	2	2	4	2	1	3	2	1	2	1	2	4	/	/	/
NC-5173	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	/	/	/
ON-745	2	2	6	-	-	-	2	2	a	2	2	a	-	-	-	-	-	-	-	-	-	-	-	-	2	2	6
OEAA-2198	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	1	2
OL-67	1	1	1	-	-	-	-	-	-	-	-	-	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1
OE4A-637	1	2	4	1	2	4	1	2	4	1	2	6	1	2	3	1	4	4	1	4	5	1	2	4	1	2	2
OE4A-729	2	2	5	-	-	-	-	-	-	-	-	-	1	1	3	1	2	2	1	1	3	3	2	5	2	2	2
SN-114	1	3	3	4	3	5	1	5	5	1	1	5	1	1	1	2	3	3	1	3	4	1	1	3	1	1	1
SF-239	3	1	3	3	1	3	2	1	3	3	1	3	-	-	-	3	1	3	2	1	3	2	2	3	2	1	3
WP-6530	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	2	1	1	1	1	6	2	/	/	/
WP-7182	3	2	4	3	3	4	4	2	4	3	3	4	2	4	4	3	3	4	3	3	4	1	1	4	/	/	/
WP-10302	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1
WP-10363	-	-	-	-	-	-	-	-	-	/	/	/	2	2	2	-	-	-	-	-	-	-	-	-	/	/	/
WP-10547	-	-	-	-	-	-	3	3	3	/	/	/	3	3	3	-	-	-	-	-	-	-	-	-	/	/	/
WP-11135	-	-	-	-	-	-	-	-	-	/	/	/	-	-	-	-	-	-	-	-	-	-	-	-	/	/	/
WP-11992	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	3	1	1	2	-	-	-	/	/	/
#Identical	9	10	23	8	8	21	7	6	23	11	7	25	9	9	28	14	15	27	10	13	28	6	6	26	12	13	24