

# SUPPLEMENTARY MATERIAL

## A Distributed Approach for Fault Detection in Swarms of Robots

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We collect here the results of the statistical tests described in Section 5 of the main paper<sup>1</sup>.

### 1 Single Fault Experiments

The permutation tests used on the results of the single fault experiments compare the means of two populations. The two hypotheses of the tests are:

$$\mathcal{H}_0 : \mu_0 = \mu_1 \text{ vs. } \mathcal{H}_1 : \mu_0 \neq \mu_1$$

where  $\mu_0$  is the mean of the first population,  $\mu_1$  is the mean of the second population,  $\mathcal{H}_0$  is the null hypothesis, and  $\mathcal{H}_1$  is the alternative hypothesis. In this case, given a behavior and a fault, the populations are the runs performed with different fault detection methods.

In Tables 1–4, we report the results: in each cell, we report the p-value of the permutation test. If, after the Bonferroni-Holm correction, the p-value remains lower than  $\alpha$ , it is reported in bold.

		<i>bact</i>	<i>lact</i>	<i>ract</i>	<i>pmax</i>	<i>pmin</i>	<i>prnd</i>	<i>rofs</i>
CRM-B	ML-B	0.7742	0.9930	0.1089	0.6722	<b>0.0002</b>	0.7696	<b>0.0002</b>
CRM-B	ML-N	<b>0.0002</b>	<b>0.0002</b>	<b>0.0002</b>	0.2965	<b>0.0002</b>	0.0821	<b>0.0002</b>
ML-B	ML-N	<b>0.0002</b>	<b>0.0002</b>	<b>0.0002</b>	0.1750	<b>0.0002</b>	0.1652	<b>0.0002</b>

Table 1: Results of the permutation tests on single fault experiments: aggregation behavior.

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<sup>1</sup> A. Carminati, D. Azzalini, S. Vantini, and F. Amigoni, A Distributed Approach for Fault Detection in Swarms of Robots, in: Proc. AAMAS, 2024.

		<i>bact</i>	<i>lact</i>	<i>ract</i>	<i>pmax</i>	<i>pmin</i>	<i>prnd</i>	<i>rofs</i>
CRM-B	ML-B	<b>0.0002</b>	<b>0.0002</b>	<b>0.0002</b>	<b>0.0002</b>	0.8294	<b>0.0002</b>	<b>0.0002</b>
CRM-B	ML-N	<b>0.0002</b>	<b>0.0002</b>	<b>0.0002</b>	<b>0.0002</b>	<b>0.0074</b>	<b>0.0002</b>	0.2917
ML-B	ML-N	<b>0.0002</b>	<b>0.0004</b>	0.0256	<b>0.0014</b>	<b>0.0077</b>	<b>0.0014</b>	<b>0.0002</b>

Table 2: Results of the permutation tests on single fault experiments: dispersion behavior.

		<i>bact</i>	<i>lact</i>	<i>ract</i>	<i>pmax</i>	<i>pmin</i>	<i>prnd</i>	<i>rofs</i>
CRM-B	ML-B	<b>0.0002</b>	<b>0.0002</b>	<b>0.0002</b>	<b>0.0002</b>	<b>0.0002</b>	<b>0.0030</b>	<b>0.0002</b>
CRM-B	ML-N	<b>0.0102</b>	<b>0.0004</b>	<b>0.0002</b>	<b>0.0014</b>	<b>0.0002</b>	<b>0.0058</b>	<b>0.0002</b>
ML-B	ML-N	<b>0.0004</b>	0.0554	<b>0.0042</b>	<b>0.0002</b>	0.5761	0.2264	<b>0.0038</b>

Table 3: Results of the permutation tests on single fault experiments: flocking behavior.

		<i>bact</i>	<i>lact</i>	<i>ract</i>	<i>pmax</i>	<i>pmin</i>	<i>prnd</i>	<i>rofs</i>
CRM-B	ML-B	<b>0.0002</b>	<b>0.0002</b>	<b>0.0002</b>	<b>0.0002</b>	0.2955	<b>0.0002</b>	<b>0.0002</b>
CRM-B	ML-N	<b>0.0002</b>	<b>0.0002</b>	<b>0.0002</b>	<b>0.0002</b>	0.2240	<b>0.0002</b>	<b>0.0002</b>
ML-B	ML-N	0.5289	0.1278	0.2753	0.4917	0.0216	0.4919	1.0000

Table 4: Results of the permutation tests on single fault experiments: homing behavior.

## 2 Multiple Faults Experiments

The permutation tests of set I, used to assess the difference in the means varying the value of  $p$ , are the same as the ones used with the results of the experiments with a single fault. In this case, given a behavior, the populations are the runs performed with a fault detection method (ML-B or ML-N) and with different values of  $p$ . We report the results of these statistical tests in Tables 5–12. The values on the y-axes and the x-axes are the values of  $p$  in the first and second population, respectively.

The permutation tests of set II, used to assess the difference in the variance varying the value of  $p$ , have the following hypotheses:

$$\mathcal{H}_0 : \frac{\sigma_0^2}{\sigma_1^2} = 1 \text{ vs. } \mathcal{H}_1 : \frac{\sigma_0^2}{\sigma_1^2} > 1$$

where  $\sigma_0^2$  is the variance of the first population,  $\sigma_1^2$  is the variance of the second population,  $\mathcal{H}_0$  is the null hypothesis, and  $\mathcal{H}_1$  is the alternative hypothesis. Also in this case, given a behavior, the populations are the runs performed with a fault detection method (ML-B or ML-N) and with different values of  $p$ . We report the results of these statistical tests in Tables 13–20.

The one-sided permutation tests of set III, used to assess the difference in the means varying the type of features, have the following hypotheses:

$$\mathcal{H}_0 : \mu_b \geq \mu_n \text{ vs. } \mathcal{H}_1 : \mu_b < \mu_n$$

where  $\mu_b$  is the mean of the results with binary features,  $\mu_n$  is the mean of the results with numerical features,  $\mathcal{H}_0$  is the null hypothesis, and  $\mathcal{H}_1$  is the alternative hypothesis. We report the results of these statistical tests in Table 21.

In Tables 5–21 we use the following criterion to fill the cells: in each cell, we report the p-value of the permutation test. If, after Bonferroni-Holm correction, the p-value remains lower than  $\alpha$ , it is reported in bold.

0.1									
0.2	0.0754								
0.3	0.0358	0.6522							
0.4	0.5152	0.2242	0.1172						
0.5	0.5188	0.1866	0.0826	0.9696					
0.6	0.6622	0.0832	0.0370	0.7408	0.7658				
0.7	0.5762	0.0026	<b>0.0010</b>	0.1366	0.1164	0.1204			
0.8	0.6650	0.0052	0.0022	0.1880	0.1656	0.2064	0.8560		
0.9	0.4354	0.0026	<b>0.0014</b>	0.0788	0.0590	0.0728	0.6176	0.5422	
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9

Table 5: Results of the permutation tests of set I: aggregation behavior with binary features (ML-B).

0.1									
0.2	0.2180								
0.3	0.0450	0.4520							
0.4	0.2498	0.9576	0.4582						
0.5	0.0022	0.0308	0.1096	0.0398					
0.6	<b>0.0006</b>	0.0054	0.0354	0.0060	0.6588				
0.7	0.0016	0.0672	0.2498	0.0720	0.4582	0.1808			
0.8	0.0036	0.0678	0.2570	0.0772	0.5300	0.2616	0.9126		
0.9	0.0082	0.1498	0.4626	0.1616	0.3308	0.1350	0.7268	0.6714	
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9

Table 6: Results of the permutation tests of set I: aggregation behavior with numerical features (ML-N).

0.1									
0.2	0.2876								
0.3	<b>0.0014</b>	0.0890							
0.4	0.0026	0.1152	0.9454						
0.5	0.0018	0.0362	0.5284	0.6228					
0.6	<b>0.0004</b>	0.0530	0.8138	0.9128	0.6540				
0.7	0.0146	0.4794	0.1382	0.2116	0.0542	0.0734			
0.8	<b>0.0008</b>	0.1214	0.7094	0.7362	0.3162	0.5232	0.1952		
0.9	<b>0.0004</b>	0.0370	0.6726	0.7912	0.7772	0.8474	0.0430	0.4018	
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9

Table 7: Results of the permutation tests of set I: dispersion behavior with binary features (ML-B).

0.1									
0.2	0.2482								
0.3	<b>0.0004</b>	0.0360							
0.4	<b>0.0004</b>	0.0370	0.8308						
0.5	<b>0.0000</b>	0.0104	0.4310	0.6160					
0.6	<b>0.0000</b>	0.0154	0.8546	0.9468	0.5062				
0.7	<b>0.0014</b>	0.1570	0.2522	0.2396	0.0624	0.1408			
0.8	<b>0.0000</b>	0.0192	0.9388	0.8712	0.4344	0.8894	0.1614		
0.9	<b>0.0000</b>	0.0052	0.4618	0.6978	0.8684	0.5698	0.0366	0.4710	
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9

Table 8: Results of the permutation tests of set I: dispersion behavior with numerical features (ML-N).

0.1									
0.2	0.3074								
0.3	0.7754	0.4082							
0.4	0.1936	0.0122	0.0566						
0.5	0.7672	0.3260	0.9592	0.0102					
0.6	0.6432	0.0840	0.3356	0.1790	0.2438				
0.7	0.3732	0.0278	0.1338	0.3824	0.0486	0.5192			
0.8	0.0778	0.0018	0.0096	0.5212	<b>0.0012</b>	0.0310	0.0594		
0.9	0.0634	<b>0.0006</b>	0.0062	0.3774	<b>0.0004</b>	0.0154	0.0356	0.7162	
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9

Table 9: Results of the permutation tests of set I: flocking behavior with binary features (ML-B).

0.1									
0.2	0.4002								
0.3	0.8968	0.4250							
0.4	0.1284	0.0152	0.0590						
0.5	0.7608	0.4766	0.8528	0.0096					
0.6	0.7046	0.1738	0.5628	0.0910	0.3362				
0.7	0.5100	0.0922	0.3456	0.1550	0.1490	0.6824			
0.8	0.0926	0.0066	0.0340	0.8804	0.0024	0.0420	0.0820		
0.9	0.0760	0.0058	0.0262	0.7598	<b>0.0012</b>	0.0352	0.0620	0.8540	
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9

Table 10: Results of the permutation tests of set I: flocking behavior with numerical features (ML-N).

0.1									
0.2	0.6602								
0.3	0.0892	0.0094							
0.4	0.5006	0.1406	0.2086						
0.5	0.0324	0.0016	0.6174	0.0642					
0.6	0.7892	0.7440	0.0110	0.1564	<b>0.0008</b>				
0.7	0.1770	0.0156	0.5482	0.4232	0.2196	0.0182			
0.8	0.4304	0.0982	0.2676	0.8650	0.0856	0.1150	0.5374		
0.9	0.1956	0.0146	0.4750	0.4462	0.1860	0.0082	0.9278	0.5744	
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9

Table 11: Results of the permutation tests of set I: homing behavior with binary features (ML-B).

0.1									
0.2	0.6428								
0.3	0.1470	0.0342							
0.4	0.7060	0.2914	0.2042						
0.5	0.0482	0.0040	0.6294	0.0520					
0.6	0.7822	0.7340	0.0322	0.3352	0.0020				
0.7	0.3410	0.0580	0.4538	0.4626	0.1626	0.0526			
0.8	0.9976	0.4882	0.0676	0.5798	0.0082	0.6150	0.1348		
0.9	0.5998	0.1606	0.2042	0.8690	0.0476	0.1452	0.4926	0.3650	
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9

Table 12: Results of the permutation tests of set I: homing behavior with numerical features (ML-N).

0.1		0.1946	0.5340	0.2400	0.0566	0.0024	<b>0.0000</b>	<b>0.0002</b>	<b>0.0000</b>
0.2	0.7924		0.8186	0.4654	0.1264	0.0058	<b>0.0000</b>	<b>0.0000</b>	<b>0.0000</b>
0.3	0.4912	0.1844		0.1656	0.0208	<b>0.0004</b>	<b>0.0000</b>	<b>0.0000</b>	<b>0.0000</b>
0.4	0.7480	0.5214	0.8264		0.2058	0.0226	<b>0.0000</b>	0.0052	<b>0.0002</b>
0.5	0.9500	0.8762	0.9754	0.7930		0.1094	<b>0.0008</b>	0.0192	<b>0.0008</b>
0.6	0.9978	0.9966	0.9998	0.9734	0.8904		0.0020	0.1198	0.0172
0.7	1.0000	1.0000	1.0000	1.0000	0.9998	0.9982		0.9022	0.8534
0.8	1.0000	0.9998	1.0000	0.9972	0.9866	0.8790	0.1018		0.2840
0.9	1.0000	1.0000	1.0000	0.9996	0.9968	0.9836	0.1470	0.7198	
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9

Table 13: Results of the permutation tests of set II: aggregation behavior with binary features (ML-B).

0.1		0.4610	0.2938	0.4474	0.4860	0.2944	0.0228	0.2162	0.2350
0.2	0.5480		0.2720	0.7104	0.8610	0.5378	0.0090	0.2428	0.1796
0.3	0.7070	0.7280		0.8390	0.9372	0.7278	0.0882	0.4586	0.4510
0.4	0.5532	0.3006	0.1636		0.6190	0.2768	0.0088	0.1258	0.1072
0.5	0.5304	0.1416	0.0740	0.3764		0.1636	0.0020	0.0568	0.0400
0.6	0.6942	0.4642	0.2660	0.7414	0.8356		0.0162	0.2256	0.1962
0.7	0.9772	0.9918	0.9140	0.9918	0.9972	0.9816		0.8962	0.9308
0.8	0.7852	0.7440	0.5266	0.8716	0.9390	0.7738	0.0984		0.4868
0.9	0.7656	0.8122	0.5480	0.8932	0.9594	0.7930	0.0604	0.5152	
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9

Table 14: Results of the permutation tests of set II: aggregation behavior with numerical features (ML-N).

0.1		0.8090	0.6536	0.6692	0.8876	0.6232	0.0198	0.1786	0.6490
0.2	0.1840		0.1834	0.5034	0.5472	0.1686	<b>0.0000</b>	0.0106	0.2154
0.3	0.3478	0.8190		0.5768	0.8342	0.4620	0.0070	0.0682	0.5348
0.4	0.3312	0.4944	0.4144		0.4856	0.3520	0.0156	0.1348	0.3750
0.5	0.1026	0.4264	0.1612	0.5330		0.1558	0.0016	0.0124	0.2014
0.6	0.3802	0.8268	0.5510	0.6510	0.8532		0.0092	0.1194	0.5634
0.7	0.9798	0.9990	0.9908	0.9832	0.9984	0.9918		0.9160	0.9726
0.8	0.8154	0.9874	0.9312	0.8768	0.9824	0.8702	0.0858		0.8628
0.9	0.3428	0.7826	0.4770	0.6416	0.8022	0.4324	0.0250	0.1338	
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9

Table 15: Results of the permutation tests of set II: dispersion behavior with binary features (ML-B).

0.1		0.7584	0.8450	0.7526	0.9600	0.6878	0.0558	0.4838	0.7668
0.2	0.2388		0.3734	0.5352	0.7790	0.2262	0.0024	0.1058	0.3090
0.3	0.1564	0.6196		0.5476	0.8722	0.2620	0.0038	0.1090	0.4326
0.4	0.2432	0.4712	0.4548		0.5124	0.3654	0.0312	0.2540	0.3594
0.5	0.0320	0.2332	0.1362	0.4948		0.0636	0.0010	0.0216	0.1064
0.6	0.3094	0.7772	0.7368	0.6574	0.9416		0.0172	0.2820	0.6286
0.7	0.9392	0.9992	0.9944	0.9650	0.9988	0.9800		0.9404	0.9786
0.8	0.5178	0.8896	0.8950	0.7402	0.9722	0.7292	0.0528		0.7798
0.9	0.2332	0.7014	0.5666	0.6424	0.8890	0.3732	0.0206	0.2160	
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9

Table 16: Results of the permutation tests of set II: dispersion behavior with numerical features (ML-N).

0.1		0.4768	0.0408	<b>0.0008</b>	<b>0.0000</b>	<b>0.0004</b>	<b>0.0000</b>	<b>0.0000</b>	<b>0.0000</b>
0.2	0.4996		0.0436	<b>0.0000</b>	<b>0.0000</b>	<b>0.0000</b>	<b>0.0000</b>	<b>0.0000</b>	<b>0.0000</b>
0.3	0.9542	0.9542		0.0024	0.0038	0.0092	<b>0.0000</b>	<b>0.0000</b>	<b>0.0000</b>
0.4	0.9998	1.0000	0.9972		0.6318	0.6186	0.0520	0.0012	0.0318
0.5	0.9998	1.0000	0.9966	0.3628		0.5226	0.0394	0.0028	0.0130
0.6	0.9990	0.9998	0.9898	0.3836	0.4896		0.0980	0.0384	0.0624
0.7	1.0000	1.0000	1.0000	0.9498	0.9618	0.9018		0.0672	0.2272
0.8	1.0000	1.0000	1.0000	0.9984	0.9968	0.9610	0.9326		0.7038
0.9	1.0000	1.0000	1.0000	0.9714	0.9880	0.9392	0.7812	0.3084	
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9

Table 17: Results of the permutation tests of set II: flocking behavior with binary features (ML-B).

0.1		0.6544	0.1530	0.0030	0.0010	0.0040	<b>0.0002</b>	<b>0.0000</b>	0.0012
0.2	0.3380		0.1172	0.0022	0.0030	0.0048	<b>0.0000</b>	<b>0.0002</b>	<b>0.0002</b>
0.3	0.8556	0.8704		0.0054	0.0166	0.0162	<b>0.0006</b>	<b>0.0000</b>	<b>0.0004</b>
0.4	0.9978	0.9988	0.9944		0.7754	0.6862	0.3200	0.0676	0.1344
0.5	0.9992	0.9964	0.9878	0.2130		0.4166	0.1194	0.0250	0.0356
0.6	0.9974	0.9942	0.9832	0.3140	0.5732		0.1940	0.0690	0.0896
0.7	0.9998	0.9998	0.9994	0.6828	0.8772	0.8150		0.0728	0.1556
0.8	1.0000	1.0000	1.0000	0.9342	0.9766	0.9328	0.9254		0.6124
0.9	1.0000	1.0000	1.0000	0.8662	0.9582	0.9056	0.8584	0.3816	
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9

Table 18: Results of the permutation tests of set II: flocking behavior with numerical features (ML-N).

0.1		0.0874	0.4476	0.1192	0.3156	0.0188	0.1104	0.1642	0.0648
0.2	0.9076		0.9940	0.9306	0.9840	0.0158	0.8290	0.7594	0.5790
0.3	0.5636	0.0044		0.0472	0.3502	<b>0.0000</b>	0.0578	0.1192	0.0234
0.4	0.8910	0.0598	0.9552		0.8292	0.0014	0.5070	0.5282	0.3238
0.5	0.6824	0.0144	0.6398	0.1664		<b>0.0004</b>	0.1680	0.2162	0.0906
0.6	0.9828	0.9822	1.0000	0.9988	1.0000		0.9966	0.9188	0.9672
0.7	0.8898	0.1702	0.9366	0.5082	0.8282	0.0052		0.5274	0.3266
0.8	0.8344	0.2470	0.8886	0.4574	0.7780	0.0790	0.4690		0.3328
0.9	0.9402	0.4366	0.9704	0.6824	0.9086	0.0310	0.6716	0.6842	
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9

Table 19: Results of the permutation tests of set II: homing behavior with binary features (ML-B).

0.1		0.1404	0.4562	0.1568	0.2606	0.0342	0.0936	0.0560	0.0560
0.2	0.8544		0.9650	0.6190	0.8840	0.0232	0.3996	0.1346	0.1504
0.3	0.5456	0.0326		0.0500	0.2490	<b>0.0000</b>	0.0146	<b>0.0006</b>	0.0016
0.4	0.8354	0.3766	0.9510		0.8006	0.0030	0.2602	0.0548	0.0658
0.5	0.7222	0.1206	0.7312	0.2002		<b>0.0002</b>	0.0586	0.0034	0.0058
0.6	0.9676	0.9744	1.0000	0.9966	1.0000		0.9628	0.6514	0.8452
0.7	0.9062	0.5988	0.9864	0.7416	0.9322	0.0354		0.1544	0.1916
0.8	0.9372	0.8656	0.9994	0.9480	0.9962	0.3560	0.8570		0.6294
0.9	0.9418	0.8492	0.9996	0.9372	0.9938	0.1498	0.8202	0.3836	
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9

Table 20: Results of the permutation tests of set II: homing behavior with numerical features (ML-N).

	<b>0.1</b>	<b>0.2</b>	<b>0.3</b>	<b>0.4</b>	<b>0.5</b>	<b>0.6</b>	<b>0.7</b>	<b>0.8</b>	<b>0.9</b>
<b>aggregation</b>	<b>0.0012</b>	<b>0.0002</b>	<b>0.0002</b>	<b>0.0002</b>	<b>0.0002</b>	<b>0.0002</b>	<b>0.0002</b>	<b>0.0002</b>	<b>0.0002</b>
<b>dispersion</b>	0.5521	0.3741	0.6091	0.7974	0.8272	0.4959	0.9292	0.9994	0.9824
<b>flocking</b>	<b>0.0114</b>	<b>0.0006</b>	<b>0.0004</b>	<b>0.0002</b>	<b>0.0002</b>	<b>0.0002</b>	<b>0.0004</b>	<b>0.0010</b>	0.0966
<b>homing</b>	0.8720	0.9832	0.6480	0.6560	0.5735	0.9996	0.5265	0.1072	0.0680

Table 21: Results of the permutation tests of set III.