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Parametric Jumping Dataset on the RHex Robot

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Abstract
This report presents the apex state achieved after performing a variety of jumps with the XRL robot. A full account of the behaviors and the theoretical basis is given in another paper, this document is intended to simply provide higher resolution copies of those figures, and present the results in numerical form.

Keywords
Legged Robot, Jumping, Leaping, Flipping, RHex

Disciplines
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Parametric Jumping Dataset on the RHex Robot

Aaron M. Johnson and D. E. Koditschek

This report presents the apex state achieved after performing a variety of jumps [1] with the XRL robot [2]. A full account of the behaviors and the theoretical basis is given in [1], this document is intended to simply provide higher resolution copies of those figures, and present the results in numerical form. Videos of example jumps, as well as jumps used in complete behaviors, are available in that document's video attachment.

As explained fully in [1], the jumps are split up into four leg strategies corresponding to forward $(+)$ or reverse $(-)$ application of torque in the front and rear motors. So for example the $(+,-)$ strategy has the front legs pushing forward (i.e. the same direction as normal running), while the rear legs are pushing backwards (i.e. up on their toes). Within each strategy, the relative leg timing t_2 parameterizes the possible jumps, where $t_2 < 0$ implies the rear leg pushing first, and $t_2 > 0$ implies the front leg pushing first.

The forward leap, $(+,+)$, was featured in [1], and so in addition to a larger copy of Figure 3, additional test data was collected to provide a more careful sampling of the leg coordination timing. Therefore Table I has more than twice the entries as the other tables or shown in Figure 3.

The reverse jump, $(-,-)$, which is typically a backflip, is shown in Figure 4a and Table II. As the robot was often more than half way through a flip at apex, the motion capture system was unable to continue tracking the robot. Therefore some velocity entries are missing, and the corresponding apex states should be taken to be "highest observed," while the true apex may be slightly higher. Also note that the $t_2 = -0.161$ jump pitch reading is erroneous, a review of the high speed video puts the true pitch at about $-90°$. Finally, the $t_2 = 0.092$ and $t_2 = 0.136$ appear to be outliers, which upon review of the high speed video reveals that one of the front legs (which are pushing before the rear legs, as $t_2 > 0$) got stuck on the frame, as noted for the $(-,+)$ strategy in [1].

There are two strategies where the legs fight: $(+,-)$, where the robot jumps more or less vertically into the air, is presented in Figure 4b and Table III; and $(-,+)$, where the robot typically flips over, is presented in Figure 4c and Table IV. The $(-,+)$ results have similar issues to $(-,-)$, with regards to measurement during inversion and front legs contacting the frame.

References

[1] A. M. Johnson and D. E. Koditschek, "Toward a vocabulary of legged leaping," in *Robotics and Automation, Proceedings of the IEEE International Conference on*, 2013, submitted.

[2] G. C. Haynes, J. Pusey, R. Knopf, A. M. Johnson, and D. E. Koditschek, "Laboratory on legs: an architecture for adjustable morphology with legged robots," in *Unmanned Systems Technology XIV*, vol. 8387, no. 1. SPIE, 2012, p. 83870W.

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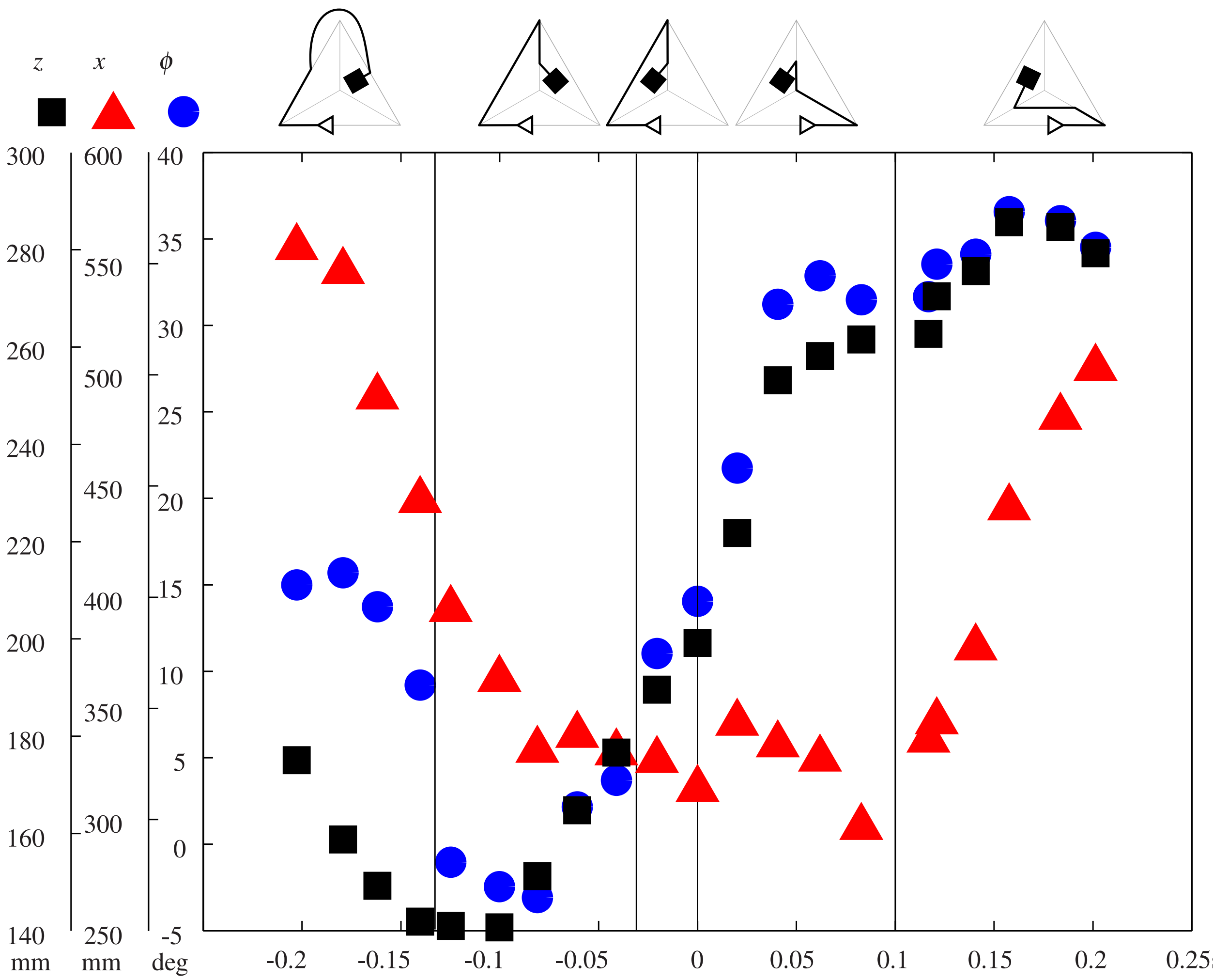

Fig. 3: Apex height (black square), displacement (red triangle), and pitch (blue circle) for $(+, +)$ jumping at various relative leg timings.

t_2 (s)	z (mm)	x (mm)	ϕ (deg)	$\dot{x}$ (mm/s)	$\dot{\phi}$ (deg/s)
-0.203	175.1	557.4	15.0	1313.6	-77.3
-0.192	168.6	552.6	16.3	1419.9	-67.6
-0.179	158.8	546.6	15.7	1378.1	-14.7
-0.171	154.7	517.2	15.7	1876.2	32.8
-0.162	149.3	490.2	13.7	1780.0	94.1
-0.152	146.5	489.2	14.1	1788.4	84.0
-0.140	141.9	443.6	9.2	2441.7	222.4
-0.128	141.9	430.7	4.6	2049.0	190.7
-0.125	141.0	394.6	-1.0	2112.7	196.3
-0.112	143.7	392.6	-1.2	2088.6	186.5
-0.111	141.4	373.2	-2.5	2086.0	177.8
-0.100	140.7	363.2	-2.5	2085.6	176.9
-0.091	148.4	347.6	-3.1	2007.6	138.1
-0.081	151.3	331.4	-3.1	1981.9	126.1
-0.071	158.0	330.3	-1.3	1941.4	109.2
-0.071	159.1	334.6	-1.9	1945.8	100.6
-0.061	164.8	338.0	2.2	1934.7	107.7
-0.055	170.2	312.2	1.7	1864.6	87.5
-0.041	176.6	330.1	3.7	1856.4	80.6
-0.031	178.5	320.1	6.6	1821.5	79.8
-0.021	189.6	326.7	11.0	1870.2	90.3
-0.010	189.8	311.2	11.7	2402.4	108.4
0.000	199.2	313.7	14.1	1749.4	82.4
0.010	199.5	305.4	16.1	2055.2	106.7
0.020	221.8	343.4	21.8	1803.2	67.8
0.030	250.4	355.1	29.2	1635.0	61.6
0.041	253.2	333.8	31.2	1492.9	41.2
0.051	254.2	334.0	32.0	1423.4	37.3
0.062	258.1	327.3	32.9	1356.1	15.1
0.071	258.6	303.2	32.0	1398.4	69.8
0.081	258.2	311.1	31.2	1338.6	54.7
0.083	261.6	296.6	31.5	1355.4	73.7
0.091	259.9	311.9	31.3	1555.7	61.2
0.111	263.2	322.9	31.6	1346.0	25.9
0.117	262.7	335.9	31.7	1335.7	22.2
0.121	270.5	344.1	33.5	947.2	11.8
0.131	268.4	363.8	32.8	1395.9	4.2
0.141	275.6	377.3	34.1	1441.4	-2.5
0.153	284.8	418.2	36.8	1308.3	0.0
0.158	285.7	440.4	36.6	1550.5	-1.9
0.184	284.7	481.1	36.1	1384.9	-11.4
0.191	280.8	481.1	35.1	1676.0	-28.8
0.201	279.3	503.1	34.5	1703.3	-26.6
0.208	272.5	500.6	32.9	1739.4	-33.1
0.212	272.6	503.4	32.9	1741.6	-33.8

TABLE I: Apex state for the $(+,+)$ jumps at various relative leg timings, including additional trials not show in Figure 3.

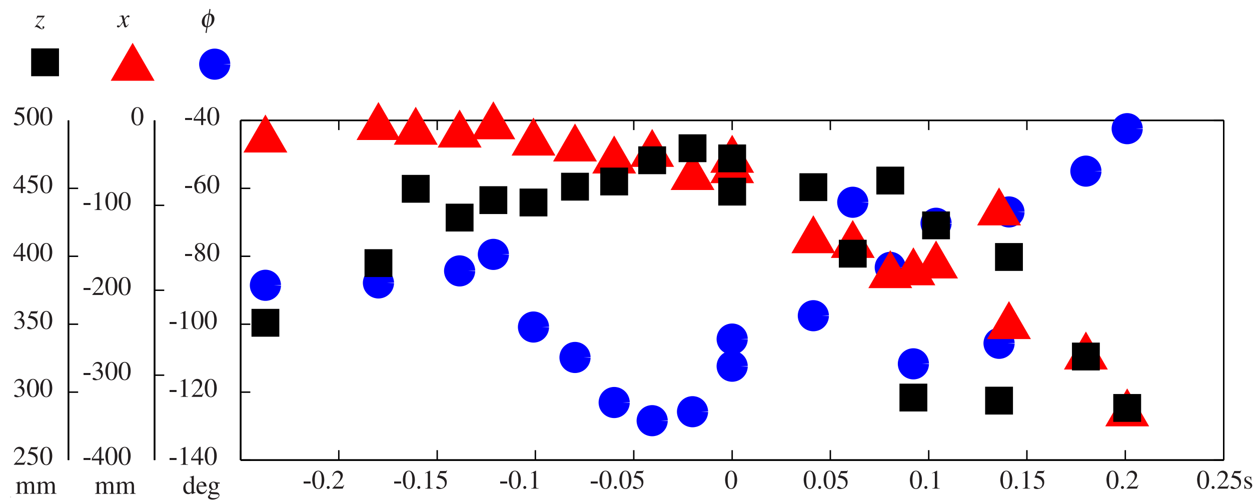

Fig. 4a: Apex height (black square), displacement (red triangle), and pitch (blue circle) for $(-,-)$ jumping at various relative leg timings.

t_2 (s)	z (mm)	x (mm)	ϕ (deg)	$\dot{x}$ (mm/s)	$\dot{\phi}$ (deg/s)
-0.237	351.0	-23.0	-88.6	114.3	-40.5
-0.180	394.8	-8.2	-87.9	61.3	-106.6
-0.161	449.6	-13.7	-219.5	108.9	16.2
-0.139	428.3	-17.2	-84.3	109.1	-203.5
-0.121	441.3	-7.4	-79.4	37.5	-204.2
-0.101	439.5	-26.5	-100.9	145.6	331.6
-0.080	451.2	-33.4	-109.8	117.6	365.6
-0.060	455.0	-47.6	-123.1	*	*
-0.041	470.5	-39.7	-128.4	*	*
-0.020	479.4	-67.1	-125.8	*	*
0.000	471.9	-46.8	-112.4	158.5	254.2
0.000	447.5	-59.1	-104.4	231.0	284.2
0.041	450.8	-141.6	-97.6	409.4	-44.0
0.061	401.9	-147.1	-64.1	553.1	-60.8
0.081	455.6	-182.8	-83.3	653.6	-159.5
0.092	295.9	-179.2	-111.7	868.7	32.2
0.104	422.6	-171.2	-70.3	589.2	-123.1
0.136	293.7	-108.7	-105.6	574.6	14.5
0.141	399.4	-242.7	-67.0	898.1	-221.6
0.180	326.1	-278.5	-55.0	1038.8	-178.0
0.201	288.3	-345.5	-42.4	1547.7	-241.8

TABLE II: Apex state for the $(-,-)$ jumps at various relative leg timings.

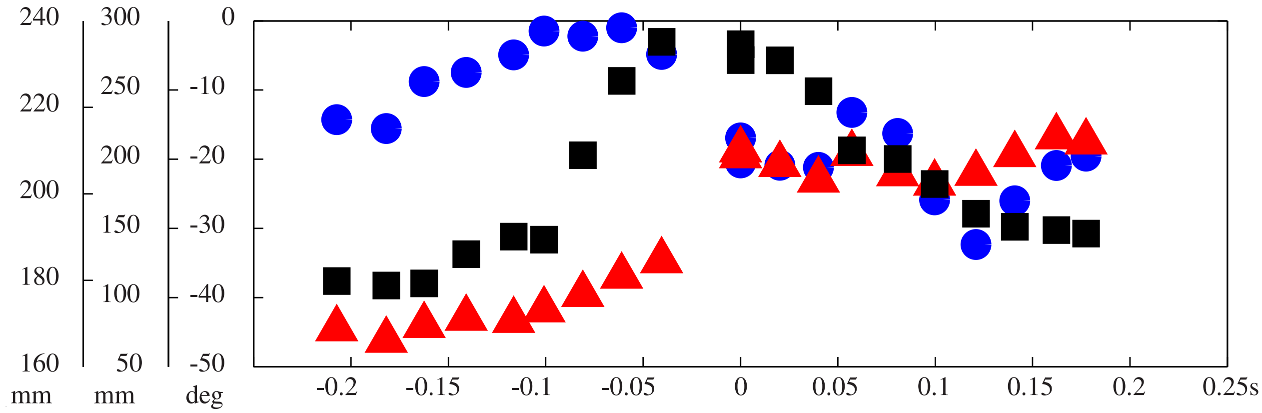

Fig. 4b: Apex height (black square), displacement (red triangle), and pitch (blue circle) for $(+,-)$ jumping at various relative leg timings.

t_2 (s)	z (mm)	x (mm)	ϕ (deg)	$\dot{x}$ (mm/s)	$\dot{\phi}$ (deg/s)
-0.207	179.8	77.5	-14.3	751.5	392.3
-0.182	178.8	69.1	-15.6	844.7	347.6
-0.162	179.3	79.8	-8.8	853.5	314.5
-0.141	186.1	85.1	-7.4	952.8	318.6
-0.117	190.1	83.6	-4.9	751.3	210.4
-0.101	189.4	91.2	-1.5	682.3	152.3
-0.081	208.9	102.3	-2.2	660.9	102.2
-0.061	226.1	115.5	-1.0	670.1	99.1
-0.041	235.1	126.6	-4.8	668.6	51.8
0.000	234.6	206.8	-20.5	679.4	-74.4
0.000	230.9	202.5	-16.9	944.4	-72.3
0.020	230.9	196.4	-20.9	883.9	-108.6
0.040	223.8	185.1	-21.2	848.6	-100.8
0.057	210.0	204.2	-13.2	1067.7	-4.5
0.081	208.1	189.5	-16.3	803.6	-27.8
0.100	202.3	182.7	-25.9	874.4	-69.7
0.121	195.4	189.8	-32.3	969.8	-67.5
0.141	192.4	203.5	-26.0	959.3	-30.5
0.162	191.6	216.2	-20.9	926.0	-11.3
0.177	190.8	212.5	-19.5	854.4	-23.5
0.266	188.7	279.6	-41.5	656.9	2.8

TABLE III: Apex state for the $(+,-)$ jumps at various relative leg timings.

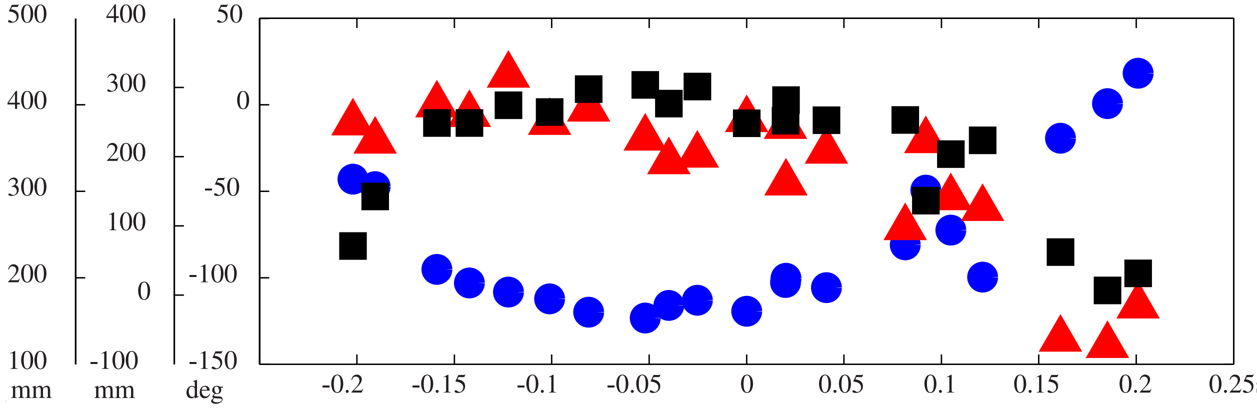

Fig. 4c: Apex height (black square), displacement (red triangle), and pitch (blue circle) for $(-,+)$ jumping at various relative leg timings.

t_2 (s)	z (mm)	x (mm)	ϕ (deg)	$\dot{x}$ (mm/s)	$\dot{\phi}$ (deg/s)
-0.202	236.7	249.0	-43.0	382.6	-89.9
-0.191	294.0	222.7	-47.3	396.4	-92.1
-0.159	378.9	274.9	-95.1	*	*
-0.142	378.8	261.2	-103.0	*	*
-0.122	399.4	318.1	-108.3	*	*
-0.101	391.8	249.8	-112.2	*	*
-0.081	418.2	269.1	-119.9	*	*
-0.052	422.9	227.2	-123.3	*	*
-0.040	401.5	192.8	-116.0	*	*
-0.025	421.3	202.5	-113.0	*	*
0.000	378.8	253.9	-119.4	705.1	275.7
0.020	381.8	243.9	-102.7	*	*
0.020	405.5	162.1	-100.3	414.6	264.2
0.041	382.2	208.0	-105.8	458.8	258.4
0.081	382.5	97.6	-81.0	282.1	-136.5
0.092	289.1	223.2	-49.4	634.0	39.6
0.105	343.1	141.0	-72.4	546.6	-113.4
0.121	358.9	125.4	-99.6	310.0	130.8
0.161	229.7	-63.5	-19.3	592.9	-134.7
0.185	185.2	-72.9	0.8	389.3	-63.4
0.201	205.1	-15.7	18.3	542.4	-35.6

TABLE IV: Apex state for the $(-,+)$ jumps at various relative leg timings.