Supplement for: From Adaptive Locomotion to Predictive Action Selection – Cognitive Control for a Six-Legged Walker

Authors

M. Schilling,[1]* J. Paskarbeit,[2] H. Ritter,[1] A. Schneider,[2] H. Cruse[3]

* - corresponding author: Malte Schilling, email: mschilli@techfak.uni-bielefeld.de

Results C: Variation of starting posture

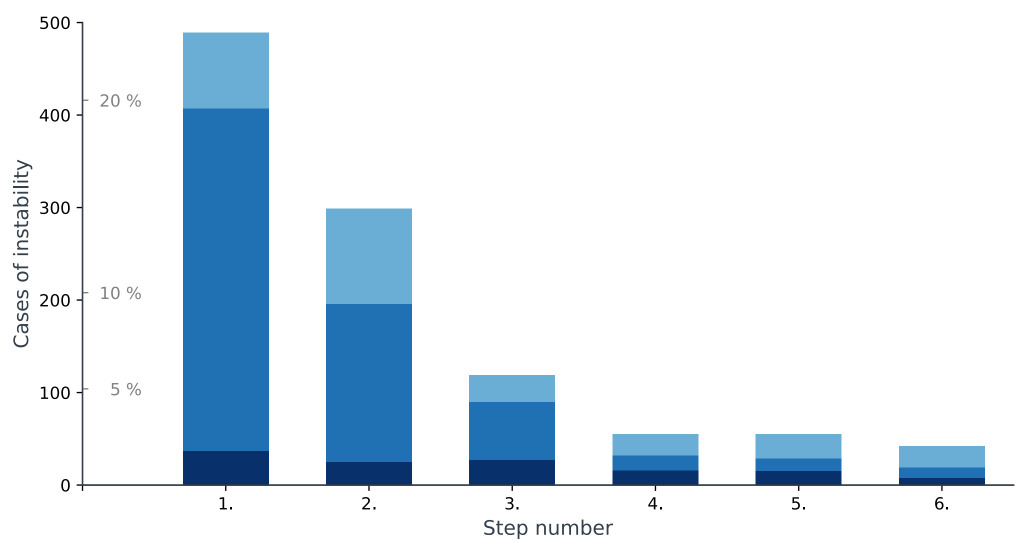
We tested systematic variations of the starting posture, at first for the decentralized architecture without using the cognitive expansion to obtain a coarse estimate of how many different starting positions lead to a stable walking pattern. The results are shown below (Fig. S4, table S2, S3) for fast and intermediate velocity. In a second step, we compared this to the architecture that includes the cognitive expansion and analyzed how the cognitive expansion dealt with the problematic cases. These results are given in the main text (Results, third series of experiments) and below (Fig. S5 and corresponding text) for fast velocity.

For each leg four different starting postures were assumed that were equally spaced from the front (anterior extreme position) towards the back (directly in front of the posterior extreme position). This poses a quite challenging task for a controller, as in many cases phases between leg controllers initially differed substantially from a typical, stable walking pattern. Overall, we ended up with 2080 different starting postures (4^6 minus all symmetric configurations with respect to the body axis). The simulated robot was set into the different starting postures and the controller took over control with a defined velocity. A posture was determined unstable when the center of gravity left the polygon spanned by the standing legs.

To illustrate the difficulty of the task: in normal walking (at a fast velocity) neighboring controllers are assumed to be in anti-phase relation. In contrast, from the 2080 initial postures, 1216 are defined with in phase relations between neighboring legs (even when excluding middle leg symmetries still 928 initial postures are characterized by phase relations that would cause instabilities when maintained during walking).

As shown in Fig. S4a,b and tables S2, S3 the number of instabilities, and correspondingly the durations of instabilities decreased strongly during the first couple of steps (data from 2080 different starting positions). After three steps, mostly only brief static instabilities could be observed. For an intermediate walking velocity (Fig. S4b, table S3), there are less frequent instabilities, but the same trend can be observed: over time the controller emerges towards stable gaits.

a)



b)

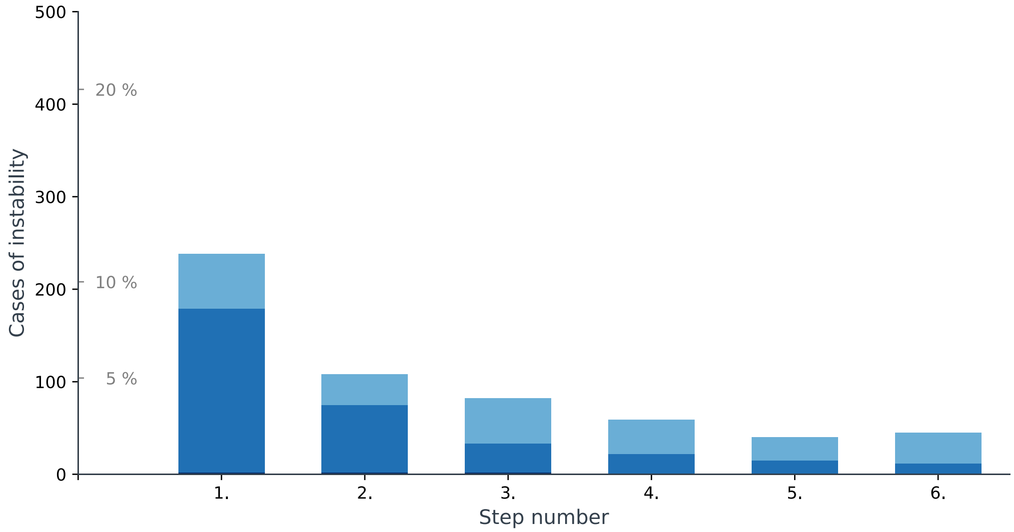


Fig. S4: **Instabilities of the control architecture** (without using the cognitive expansion) when forced into systematically varied starting postures. Abscissa: number of robot steps. Light Blue: duration of instabilities between 10 ms and 100 ms; blue: duration longer than 100 ms, but only appearing during a single step cycle of that particular leg; dark blue: long instabilities (longer than 100 ms) and found in subsequent steps of the walking robot. a) for high velocity (0.020). b) for intermediate velocity (0.016).

Table S2: Cases of instability for tripod (fast) walking.

Step number	**1**	**2**	**3**	**4**	**5**	**6**
Duration of instability						
10–90 ms (light blue)	82	103	29	23	26	23
Instability >= 100 ms (but single step) (blue)	370	171	63	16	14	11
Instability spanning mult. steps (dark blue)	37	25	27	16	15	8

Table S3: Cases of instability for intermediate velocity.

Step number	**1**	**2**	**3**	**4**	**5**	**6**
Duration of instability						
10–90 ms (light blue)	59	33	49	37	25	33
Instability >= 100 ms (but single step) (blue)	177	73	31	21	14	11
Instability spanning mult. steps (dark blue)	2	2	2	1	1	1

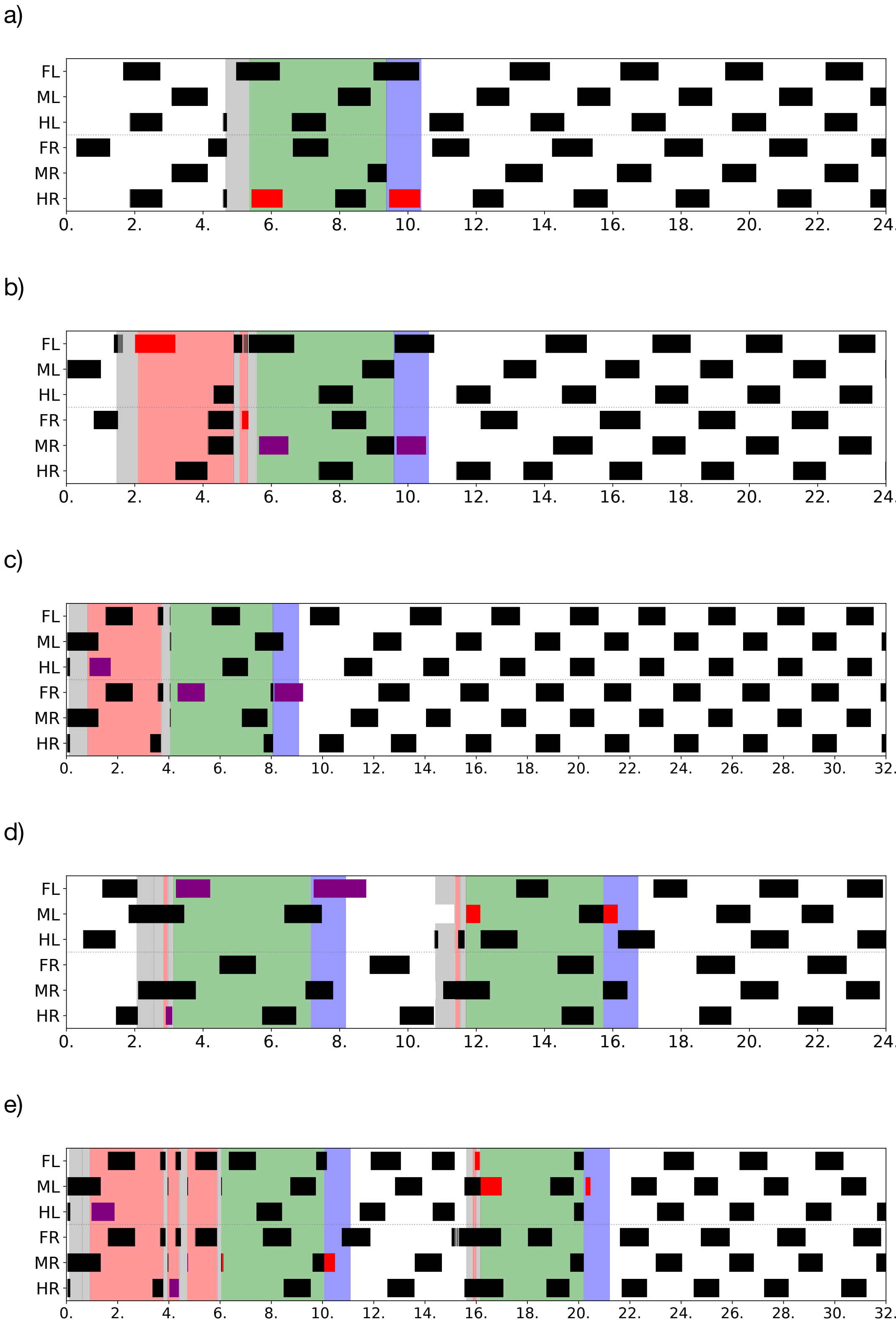


Fig. S5: Examples of difficult starting postures. In the color shaded areas, the cognitive expansion took over: grey represents initially stopping and selecting an action, light red shows unsuccessful testing of that action in internal simulation applied on the body model and green shows a successful internal simulation which was finally applied on the dynamically simulated robot (blue area). Backward swing movements in red. Forward swing movements selected by cognitive expansion in purple. For details see text.

As mentioned above, in the second step of these experiments the behavior of the complete system—including the cognitive expansion—was analyzed. From the 2080 starting positions, 617 cases triggered the cognitive expansion. In 70.3 % the reactive network was sufficient to lead to stable walking behavior. For 28.9 % the cognitive expansion found a solution, while in the remaining 0.7 % no solution has been found.
When the disturbed cases that triggered the cognitive expansion were run for 24 seconds, in 540 cases a solution was found by the cognitive expansion. Often, internal simulation was triggered multiple times in the disturbed cases that triggered the cognitive expansion (from the overall 617 planning runs, 111 required a second planning phase and 33 even three planning phases). In the remaining 77 cases planning was still running after the 24 sec given. We ran the 77 simulation runs with unfinished planning again, but now for a longer time (of 32 s): In 34 cases the added time was sufficient to successfully finish internal simulation and continue walking. In 28 reruns the problematic situation was already resolved by the first internal simulation, as due to the stochasticity of the selection process, a different behavior was selected compared to the first run of the respective starting posture. In 2 further cases, there was still an internal simulation running at the end of the 32 seconds. In the remaining 13 cases, in which the controller did not find a solution that allowed to continue stable walking, the walker got stuck in the selection process (either by running out of choices or in some cases the winner-take-all network had multiple competing values which were too close together to converge in the allocated time window).

In Fig. S5 five examples are shown that illustrate the impressive adaptivity of the approach. In Fig. S5 a), hind legs were initially in phase which would result in a short instability as the robot tries to lift both hind legs at the same time during the second step. Immediately, the cognitive expansion tested a swing backward of HR, which solved the problem (successful internal simulation is shown in green area) and therefore the solution was applied to the simulated robot (blue area).
b) A long instability occurred as the robot tried to lift the front left leg (FL) while front right (FR) already performed swing movement. Therefore, the robot stopped walking and started search (grey area). But the swing movement of the front right leg was finished immediately (within grey area). A first trial (swing backward of FL, red) was not successful as it led hind left leg, front right leg and middle right leg to lift simultaneously (light red area). In a second trial, cognitive expansion tried to reposition FR backwards, again without success. The third trial (swing movement to the front at MR, marked purple, selected by cognitive expansion) was successful (green area). As can be seen, the front left leg also performs a swing movement which is still triggered by the front left leg being far to the back of its working range making this movement necessary. This solved the instability, which did not occur later-on again as both front legs were moved in a more or less anti-phase relation by the intervention. The solution was applied to real walking (blue area).
c) When this case had first been tested without access to the cognitive expansion, long instabilities occurred over several steps (not shown) because, immediately after initialization, swing movements for middle left leg, hind left leg, middle right and hind right leg were started. During a run of 16 s altogether instabilities for 4.56 s have been observed. If, however, as shown in Fig. S5c, the test was repeated with the cognitive expansion being available, the system was triggered by the problem detector in the hind right leg and the cognitive expansion was activated. In the first trial (left grey area followed by light red area), the cognitive expansion tried unsuccessfully to reposition the hind left leg (swing movement to the front, marked by purple). In a second trial (starting in second grey area, followed by green area), the problem was resolved by a swing movement to the front of FR (marked by purple). As the FR leg does not itself contribute to stability at the back, this appears a surprising solution: but when looking at the footfall patterns and data more closely, it becomes apparent that this solution emerges from the decentralized structure and coordination rules: selecting a swing movement for FR inactivated coordination rule 3 from FR to MR which would have elicited the early swing movement of MR. Last, this solution is applied for real walking (blue area).
d) Multiple internal simulations: During the first steps the robot tried to lift MR, while HR and ML have already been lifted, which led to an instability (grey area followed by light red area). Importantly, during stopping of the simulated robot, MR and ML did not finish their swing movements, but the HR finished its swing movement (as it was already nearly finished). This allowed the cognitive expansion to select HR (first trial, grey area followed by light red area) to try another swing movement of HR to the front (marked purple) which caused another instability. In the second trial, the cognitive expansion selected a swing movement of FL to the front (marked purple) which provides a solution. Although this first instability could be solved, after about 4 s of walking (at about 11 s) the same instability occurred during the next step of the robot. This is not surprising as the phase relations between the hind legs and middle legs had not been altered by the intervention of the cognitive expansion, and, in this case, the decentralized structure could not resolve the problem over the short time span. But during this second internal simulation the cognitive expansion selected a swing backwards of ML (green

shaded area, swing shown in red) which resolved the instability and was then applied on the robot (blue shaded area).

e) In the initial leg configuration, both middle and both hind legs were placed very far back and, therefore, immediately tried to produce swing movements leading to instability. Initially, the cognitive expansion tried, without success, multiple different actions (first trial, swing movement to the front of HL, marked purple; second trial, swing movement to the front of HR, marked purple; third trial, short swing movement to the front of MR at about 5 s, marked purple), but none of these solved the problem. The system found as a solution swinging the right middle leg backwards (at about 6 s, as the leg was already in swing, but far to the back of the working range, this short swing movement, marked red, is difficult to recognize). This successful movement (green area) is then applied on the robot (blue area, about 10 – 11 s). At this point, a difference is notable between internal simulation and the (dynamically simulated) robot: switching direction of the ongoing swing movement of MR takes much more time in the dynamic simulation (blue area, MR, red). Nonetheless, this provides a solution for the problem at hand. Some steps later-on, at about 16 s, a further planning stage is required to resolve the difficult initial leg configuration. During this planning stage, first, the cognitive expansion tried to move the front left leg backwards (shown as a red bar at around 16 seconds in small, red shaded area) which lead again to an instability with the robot threatening to tilt to the front. Secondly, the middle left leg (ML, red, in light red area) was moved backwards. This was then successfully tested also on the robot leading to the emergence of a stable walking pattern.