1 Supplemental material

Here we provide a mathematical description of the whisking pattern generation algorithms, some additional implementation details of the Shrewbot architecture, and a derivation of the measures of contact quality used in the analysis of the main text.

1.1 Whisking pattern generation

To generate a base whisking pattern that can provide a substrate for models of active touch modulation, the whiskers of Shrewbot are controlled by a single square wave oscillator with a fixed duty cycle of 70%. Apart from this common drive signal, which is sent to all 18 whiskers simultaneously, each whisker is separately controlled. Contact belief is obtained by applying threshold and saturate operations to the drive signal, which is sent to all 18 whiskers simultaneously, each whisker is separately controlled. Contact belief is of Shrewbot are controlled by a single square wave oscillator with a fixed duty cycle of 70%. Apart from this common
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Let \( \theta^\text{hmin} \) and \( \theta^\text{hmax} \) denote, respectively, the minimum and maximum whisker protraction angles that the hardware offers (these are the same for all whiskers, at 75 and 175 degrees, respectively). Next, let the instantaneous ‘target’ minimum and maximum protraction angles for the \( w \)th whisker be denoted by \( \theta^\text{min}_w(t) \) and \( \theta^\text{max}_w(t) \); these are derived from \( \theta^\text{hmin} \) and \( \theta^\text{hmax} \) based on the recent modulation received by the WPG for that individual whisker, as follows. \( \theta^\text{min}_w(t) \) is always set equal to \( \theta^\text{hmin} \), so that the whiskers are always attempting to recover to \( \theta^\text{hmin} \) during the OFF period of the oscillator. For each whisker, we define a constant ‘nominal’ (unexcited) and ‘excited’ protraction angle, denoted \( \theta^\text{nom}_w \) and \( \theta^\text{exc}_w \), respectively. These parameters are defined, qualitatively, based on biological observations as summarised above. Specifically, during normal free exploratory whisking (in the absence of attention to nearby surfaces) the more caudal whiskers move less than those that are more rostral. Thus, we define \( \theta^\text{nom}_w \) as being 40, 60 and 80% of maximum hardware protraction, for the caudal, central and rostral columns, respectively. When investigating surfaces, all whiskers are brought forward towards the object. We model this by defining \( \theta^\text{exc}_w \) as being 90, 95 and 100% of maximum hardware protraction for caudal, central and rostral columns during investigation of objects. Note that the exact values of these parameters do not affect the qualitative nature of modulated whisking.

The dynamics of \( \theta^\text{max}_w(t) \) are given by

\[
\frac{d\theta^\text{max}_w(t)}{dt} = (\theta^\text{exc}_w - \theta^\text{max}_w(t))f_S\alpha(t) + (\theta^\text{nom}_w - \theta^\text{max}_w(t))/\tau_\alpha
\]

where \( \alpha(t) \) is the ‘excite’ modulation strength, common to all whiskers, \( \tau_\alpha = 1s \) is the excite recovery time constant, and \( f_S \) is the integration sample rate. Thus, when \( \alpha(t) \) is unity, \( \theta^\text{max}_w(t) \) goes to \( \theta^\text{exc}_w \) in one integration sample time, and stays there; when \( \alpha(t) \) is zero, \( \theta^\text{max}_w(t) \) recovers towards \( \theta^\text{nom}_w \) with time constant \( \tau_\alpha \).

The dynamics of the instantaneous protraction angle of the \( w \)th whisker, \( \theta_w(t) \) are governed by separate equations during the ON and OFF periods of the drive oscillator. In OFF, the dynamics are given by

\[
\frac{d\theta_w(t)}{dt} = (\theta^\text{min}_w(t) - \theta_w(t))/\tau_\text{drive}
\]

such that \( \theta_w(t) \) decays towards \( \theta^\text{min}_w(t) \) with time constant \( \tau_\text{drive} \), which governs the response of the instantaneous whisker angle to the drive signal. During ON, the dynamics are given by

\[
\frac{d\theta_w(t)}{dt} = (\theta^\text{exc}_w - \theta_w(t))/\tau_\text{drive}
\]

such that \( \theta_w(t) \) increases towards \( \theta^\text{exc}_w \) with time constant \( \tau_\text{drive} \).
\[
\frac{d\theta_w(t)}{dt} = \frac{(\theta_{tgtw}(t) - \theta_w(t))}{\tau_{drive}} \quad (4)
\]

\[
\theta_{tgtw}(t) = \min(\theta_{tgtmaxw}(t), \theta_{tgtdesw}(t)) \quad (5)
\]

\[
\theta_{tgtdesw}(t) = \theta_{maxw}(t) + \beta_w(t)(\theta_{minw}(t) - \theta_{maxw}(t)) \quad (6)
\]

such that \(\theta_w(t)\) decays towards \(\theta_{tgtw}(t)\) with time constant \(\tau_{drive}\). In the unmodulated case, the target maximum \(\theta_{tgtmaxw}(t)\) is equal to 180 degrees, and the inhibition strength \(\beta_w(t)\) is equal to zero; thus, \(\theta_{tgtw}(t)\) is equal to \(\theta_{maxw}(t)\).

The model of excitatory feedback is given by

\[
\alpha(t) = min(g_{\alpha max}(c_w), 1.0) \quad (7)
\]

where \(g_{\alpha}\) is the excitatory gain and \(c_w\) is the contact belief of the \(w\)th whisker. Thus, contact on any whisker drives excitation of all whiskers. Two models of inhibitory feedback are used (denoted ‘feedback’ and ‘release’), both of which use the same value for \(\beta_w(t)\) given by

\[
\beta_w(t) = min(g_{\beta c_w}, 1.0) \quad (8)
\]

where \(g_{\beta}\) is the inhibitory gain. Thus, contact on one whisker drives inhibition of only that whisker. In the ‘feedback’ model, only the above equation is used, and \(\theta_{tgmaxw}(t)\) is fixed at 180 degrees. In the ‘release’ model, \(\theta_{tgmaxw}(t)\) is also reduced during the oscillator ON-OFF cycle according to

\[
\theta_{tgmaxw}(t) = \min(\theta_{tgmaxw}(t - T_S), \theta_{maxw}(t) + \beta_w(t)(\theta_{w}(t) - \theta_{maxw}(t))) \quad (9)
\]

where \(\theta_{w}(t)\) is the actual position of the whisker at time \(t\) as reported by the odometry and \(T_S = 1/f_S\) is the integration sample time. \(\theta_{tgmaxw}(t)\) is also reset to 180 degrees at the beginning of each ON period. Thus, using the ‘release’ model, the commanded whisker position is limited to not exceed a measured whisker position which led to \(\beta_w(t) = 1\) (absolute contact belief) for the remainder of that oscillator ON-OFF cycle.

Note that both inhibitory modulation models are intra-whisk; that is, contact during whisk \(n\) has no effect on behaviour during whisk \(n + 1\). In contrast, the excitatory modulation model is inter-whisk, with the period of effect governed by the recovery time constant, \(\tau_{\alpha}\). Finally, since the first-order dynamics of \(\theta_w(t)\) allow through the discontinuities in the drive signal which excites resonances in the controller/mechanics system, \(\theta_w(t)\) is low-pass filtered at \(3f_W\) (3rd order Butterworth), with \(f_W\) the whisking frequency, before being passed to the whisker position controllers.

The WPGs tested on the robot can now be defined as follows: 
- **WPG1** has \(g_{\alpha} = 0\) and \(g_{\beta} = 0\),
- **WPG2** has \(g_{\alpha} = 10\) and \(g_{\beta} = 0\),
- **WPG3** has \(g_{\alpha} = 10\) and \(g_{\beta} = 3\) using the ‘feedback’ model and
- **WPG4** has \(g_{\alpha} = 10\) and \(g_{\beta} = 3\) using the ‘release’ model.

### 1.2 Control architecture

Each actuated degree of freedom of the Shrewbot platform is controlled locally using standard software-based PD position controllers implemented using embedded microprocessors. The neck and head motors and sensors are interfaced to a (Linux) miniITX computer via a low latency FPGA bridge to USB 2.0 (bulk transfer mode, 500\(\mu\)s update period) and each whisker microcontroller communicates via a 5 Mbps SPI bus to the USB bridge electronics. The desired position for each axis is updated by the miniITX computer which maintains the main control architecture of the robot.
and controls the global synchronisation of the platform during each experiment. A small PC104 computer on-board
the Robotino [1] acts as a server to which the miniITX computer issues motor commands and requests odometry
and sensory data. The platform uses Lithium polymer batteries which allow up to 1 hour of mobile experiments be-
tween re-charging. The software model (including hardware interfaces) were developed within the BRAHMS modular
execution framework [2] for ease of integration and off-line development, and slaved to the FPGA clock.

References

2007.