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BIO-inspired intelligent navigation: from methodology, system theory, to behavioural science

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It is crucial for unmanned systems to determine their motion information accurately, reliably, and in real time. This function is accomplished by the autonomous navigation module of the unmanned systems. By analogy to the animals, the autonomous navigation module can be regarded as the "sensory nerve center" of an unmanned system. With the complication of application scenarios, the existing navigation technologies are facing unprecedented challenges. For example, inertial navigation is subject to error accumulation, leading to severe performance degradation in long-endurance missions. The GNSS-based navigation is vulnerable to inference, denial of service, or signal deception, which restricts its application in confrontation scenarios. The vision-based navigation, on the other hand, relies on the preset feature points, and thus is not suitable in unfamiliar and unstructured environments. These bottleneck problems can be boiled down to the lack of adaptability to disturbed, signal-denied, and unstructured environments.

Our perspective is that intelligent navigation provides a potential solution to the aforementioned challenges. By intelligent navigation, we mean that the navigation system can adapt autonomously to complex environments via intelligent learning, cognition, and prediction techniques, and thus meets the reliability and robustness requirements of unmanned systems. As the main innovation source of intelligence science, the bionics has received considerable research attention in recent years. Focusing on the navigation problems, it is noted that with billions of years of evolution, the animals have possessed superb navigation skills. By sensing the pattern of polarization of the skylight with their compound eyes, the desert ants can find their way back home after foraging for hundreds of meters in hostile environments [1]. Some flying insects like the drosophila can achieve reliable attitude determination by using neural processing units called "mushroom bodies" to fuse multi-source motion information, e.g., the inertial information sensed by the halteres, the optical information sensed by the compound eyes, and the magnetic information sensed by the magnetic compass [2]. More interestingly, it has been revealed that some nocturnally migrating songbirds, born with the geomagnetic-compass-like organ for navigation, can behaviorally respond to the environment by activating the function of magnetic field perception when they are migrating, and deactivating this function during the day when geomagnetic information is not needed [3].

Inspired by the navigation mechanism of animals and the practical demand on autonomous navigation capabilities, we believe that the intelligence of navigation should be pursued from the following three aspects (see Figure 1 for the logical relationships between them):

(i) **The intelligent estimation methodologies**, which correspond to the function of neural computation of animals, are capable of accurate and reliable fusion of the multi-source motion information;

(ii) **The intelligent sensing devices/systems**, which correspond to the function of the sensory organs of animals, are capable of collection and interpretation of the navigation information;

(iii) **The intelligent navigation behavior** resembles the decision-making behavior of the animals for optimal navigation mode in a specific scenario.

In particular, the exploration of behavioral intelligence not only addresses a critical gap in autonomous navigation, but also aims to broaden the scope of biomimetic intelligence. In addition to the embodiment design as in the "embodied AI", the bio-inspired intelligence has also focused on the neural-inspired motion state estimation algorithms so that the navigation systems can autonomously survive in the complex uncertain environments.

The estimation methodology: neural interpretation of the motion information. The motion estimation algorithm is the basis of intelligent navigation. The animals are able to determine the motion information in their nerve centers by interpreting and fusing the data from different sensory organs which are inherently vulnerable to disturbances. The intelligence of the fusion algorithm mainly manifests in the way that disturbances and uncertainties are handled. For unmanned systems, the situation is more complicated as the disturbances are physically multi-sources (external environment, internal devices, and model errors), mathematically heterogeneous (dynamic, stochastic, and norm-bounded), and affecting the navigation system in a coupled way. The disturbances with the aforementioned characteristics are called "composite disturbances". In the conventional state estimation methods, the composite disturbances are usually simplified as a lumped one so that the "single" dis-

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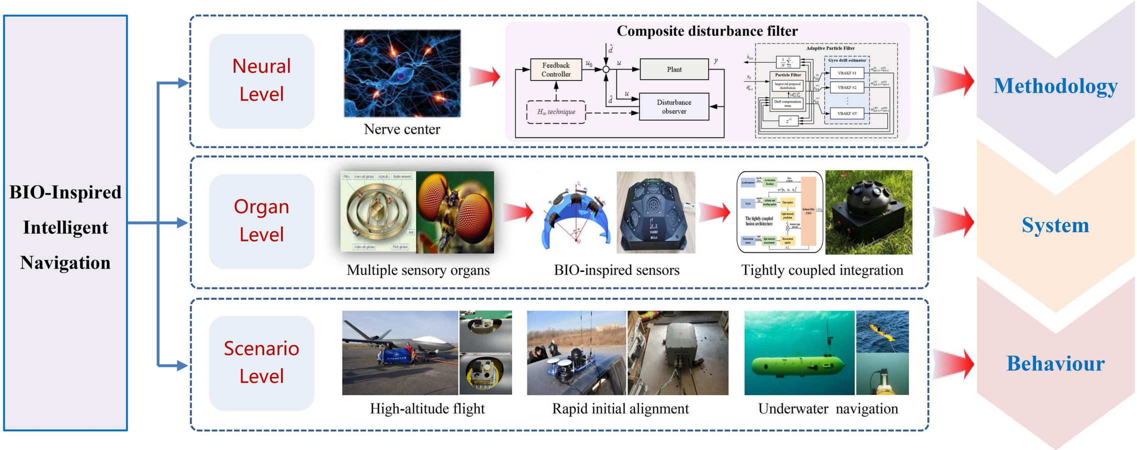

Figure 1 (Color online) BIO-inspired intelligent navigation.

turbance can be either rejected or attenuated. For example, the disturbances are regarded as a single Gaussian random variable in the celebrated Kalman filter. This "single disturbance" assumption may lead to an inaccurate, conservative, or even unreliable estimation result, severely deteriorating the navigation performance.

To overcome the limitation of "single disturbance" assumption, the composite disturbance filtering (CDF) theory has been established since the pioneering work in 2012 [4]. In the CDF, the multi-source heterogenous disturbances are dealt with according to their specific characteristics. This is achieved by refined quantification, effective separation, and simultaneous rejection and attenuation of the disturbances. First, a deeply coupled model for the navigation system with composite disturbances is established, where the dynamic, stochastic, and norm characteristics of and the causal relationship between the disturbances are fully reflected. Then, the separability of the composite disturbances is quantified, which can be regarded as a generalization of the concept of observability in traditional estimation theory. Note that the refined quantitative analysis of disturbances is also an important trend in the age of big data and big models.

Based on the refined quantification and separability analysis, the simultaneous rejection and attenuation strategy can be designed for the composite disturbances. For this purpose, a composite filter structure is employed, which normally consists of a disturbance observer module for real-time reconstruction and rejection of the unknown dynamic disturbances, and a Kalman filter/particle filter/H_∞ filter module to attenuate the Gaussian stochastic/non-Gaussian stochastic/norm-bounded disturbances [5]. In more complicated scenarios, the dynamic or stochastic knowledge of the disturbances is unavailable or incomplete. To address this challenge, advanced artificial intelligence models, such as the neural networks and the Gaussian processes, can be embedded into the CDF framework to achieve online disturbance learning and prediction. For example, an evolutionary model-based disturbance observer/predictor can be constructed by leveraging the Koopman operator to explore the latent structure of disturbances.

More recently, the idea of disturbance excitation has also been proposed, where the originally inseparable disturbances can be made separable by adding a well-designed input signal. A typical example in this aspect is the input design for an optimized UAV flight trajectory such that the sensor bias can be well separated. Up to now, the CDF has been applied to practical systems including initial alignment, integrated navigation, etc. Interested readers are referred to our recent survey paper [6] for a more comprehensive introduction. In our opinion, the disturbance excitation represents a paradigm shift in anti-disturbance estimation from the traditional "algorithm design" to the BIO-inspired "behavior design".

The navigation system: compound-eye-inspired tightly coupled integration. Many animals, such as desert ants, honey bees, monarch butterflies, and mantis shrimps, are capable of sensing the patterns of light polarization in the sky (or underwater) to achieve reliable navigation during the process of foraging and homing. The polarization vision can be obtained by the polarization-opponent (POL) neurons located in the dorsal rim area of the compound eyes. Inspired by the polarization sensing mechanism of the animals, various polarization sensors have been developed to achieve autonomous navigation in GNSS-denied environments. Most of the early-stage polarization sensors are monocular ones. To better mimic the compound-eye structure of the animals, the bio-inspired compound-eye polarization sensors have been designed with a non-coplanar "POL-type" structure [7]. With the compound-eye configuration, richer polarization information can be perceived from a wider field of view.

Furthermore, the existing polarization sensing models are based on the ideal single-scattering Rayleigh theory, which may fail to describe the practical factors such as the non-ideal atmospheric environments (e.g., stray light interferences, water vapor, water droplets, ice crystals, and aerosols) and the sensor installation errors. To address this limitation, a deeply-coupled polarization measurement model has been established for the compound-eye polarization sensor, where the uncertainty factors including stray light interferences, non-ideal weather conditions, non-vertical errors, and relative installation errors between elementary polarization units have been taken into account [8]. By this means, the environmental adaptability of the compound-eye-inspired polarization sensors has been significantly improved.

The polarization measurement alone cannot offer three-dimensional (3-D) spatial motion information. Inspired by the multiple sensory organ fusion principle of the animals, the integrated inertial/polarization navigation strategy is proposed, which mimics the halteres/compound eyes integration of flying insects for 3-D motion information acquisition. On this basis, the tightly coupled modeling and calculation approach is proposed for the integrated inertial/polarization navigation system, which enables reliable 3-D attitude determination with a clear error transmission mechanism and enhanced robustness against optical path occlusion [9].

The navigation behaviour: adaptability to multi-domain application scenarios. The animals can behaviorally respond to different navigation scenarios by adjusting their navigation strategies accordingly. Similarly, the behavioral intelligence of the autonomous navigation system has been demonstrated in multi-domain application scenarios.

- Scenario 1: The unmanned aerial vehicles. For unmanned aircraft performing high-altitude cross-domain flight tasks, the external environment would change significantly throughout the entire flight. Hence, a 3-D motion information acquisition scheme with environmental adaptability is required. Aiming at this problem, the tightly coupled inertial/polarization integration scheme can be employed. On this basis, a novel navigation strategy is proposed by mimicking the mode-switching behavior of the migrating songbirds. Specifically, adaptive navigation in the cross-domain time-varying environment can be achieved via a multi-modal switching and online parameter identification scheme. The switching decision is made according to a predefined threshold which characterizes the instantaneous observability of the navigation system. By this means, the navigation mode and model parameters can be adapted concurrently. The tightly-coupled inertial/polarization integrated navigation module developed by the Beihang research group has gone through flight tests on a hypersonic vehicle, demonstrating the practicality of the aforementioned scheme.
- Scenario 2: The ground vehicles. For ground-based weapon platforms like the missile launching vehicle, there is an urgent demand to realize rapid initial alignment of the inertial navigation systems in the GNSS-denied battlefield environment. To meet this requirement, a polarization-aided rapid initial alignment scheme is developed. Specifically, the "point-source" polarization sensor is employed instead of the "camera-based" one so as to avoid the unaffordable image processing time. Moreover, a temporal difference-based polarization measurement modeling approach is proposed to cope with the highly dynamic scenarios. In the proposed model, a direct relationship between the output of the polarization module and the inertial sensor biases has been established. By these means, the calculation procedure for initial alignment is greatly simplified, leading to a significant reduction in alignment time. Experimental tests on a missile launch vehicle show that with the polarization-aided rapid initial alignment system developed by Beihang research group, the alignment time has been shortened by almost an order of magnitude.
- Scenario 3: The underwater vehicles. Underwater navigation is a challenging technology for autonomous underwater vehicles (AUVs) as the GNSS signal underwater is weak and the marker points are not easy to deploy. Inspired by the navigation mechanism of mantis shrimps, the inertial/polarization integration scheme for underwater navigation has been proposed. In particular, the challenges brought by the mixed scattering/refraction effect resulting from cross-media (atmosphere+water) sunlight transmission as well as the wave and turbidity of water have been addressed by establishing a deeply-coupled underwater polarization measurement model [10]. Experimental tests in complex marine environments show that the underwater inertial/polarization integrated navigation system developed by Beihang research group can achieve 3-D attitude determination of the AUV with full autonomy and enhanced robustness (depth of water: $\leqslant 20$ m).

Future research directions. We believe that bio-inspired intelligent navigation should be explored from the methodology level, the system level, and the behavior level. Even though great progress has been made, there are still many interesting research directions. (1) Conducting neuro-empowerment of the navigation sensors by embedding error characteristics, vehicle dynamics, and spatiotemporal constraints into the sensing models. (2) Enhancing anti-disturbance capability, fault-tolerance, and safety of the navigation system via dynamic closed-loop uncertainty quantification. (3) Enabling cross-domain seamless transition of the navigation behavior via real-time situational cognition and system reconfiguration. (4) Enabling self-evolution of the navigation system via intelligent testing (with online disturbance excitation) and interactive optimization.

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