

OLFACTORY SENSING IN HUMAN-ROBOT TEAMING: PERSPECTIVES AND GUIDELINES

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ABSTRACT

Human-Robot Teaming (HRT) has seen significant advances with robots becoming increasingly capable of working alongside human operators in shared environments. This paper explores the potential for olfactory sensing as a bio-inspired method to enhance communication and collaboration in human-robot teams. Olfactory signals, which have long been used in human communication to express emotions and intentions, can be leveraged to create more intuitive and natural interactions between robots and humans. This perspective paper outlines the potential benefits of incorporating olfactory sensors into robots, discusses current limitations, and provides guidelines for integrating olfactory sensing into future HRT systems.

1 INTRODUCTION

Human-Robot Teaming (HRT) has become an integral part of many modern applications, where robots work alongside humans to perform complex tasks in shared environments. Traditional methods of communication, such as visual and auditory cues, are limited in their ability to convey human emotional states or nuanced intentions. This paper explores the integration of olfactory sensing into HRT, proposing a bio-inspired approach that allows robots to interpret and respond to human emotional states through scent.

Olfactory perception is one of the most ancient and phylogenetically conserved sensory systems in vertebrates, serving as a primary communication channel for survival, reproduction, and the assessment of environmental threats. Unlike visual and auditory sensory modalities, which require complex thalamo-cortical processing before eliciting emotional or behavioural responses, olfaction benefits from privileged and direct neuroanatomical access to the limbic structures of the human brain. This unique neural

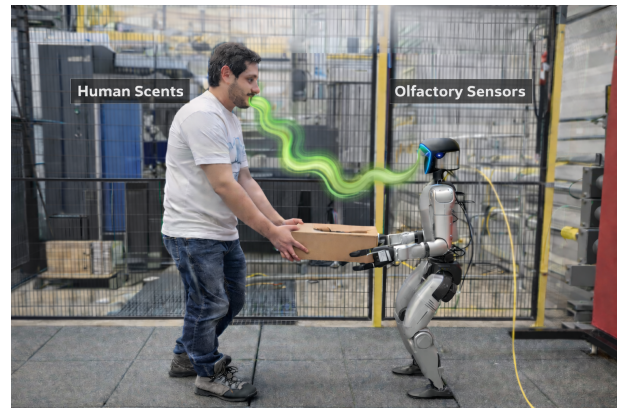


Figure 1: The idea of human-robot teaming (HRT) with olfactory sensing.

architecture allows chemical signals, including those not consciously perceived, such as putative pheromones and stress-related volatile compounds, to profoundly modulate an individual's behaviour, mood, and endocrine physiology, bypassing the filters of subjective awareness (Young, 2008).

In the context of HRT, this direct access to the limbic system could enable robots to more effectively interpret human emotional states and intentions Sanfilippo and Rano (2023). By integrating olfactory sensors into robots, we propose that robots can detect and respond to emotional cues, improving communication and collaboration in ways that traditional sensors cannot. The idea is shown in Figure 1. This paper provides a conceptual framework for integrating olfactory sensing into HRT systems, aiming to create more intuitive, empathetic, and responsive interactions between humans and robots.

The human sense of smell is not a unitary system but rather an integrated complex of parallel pathways that process qualitatively distinct information. Understanding how an odour (or a volatile hormonal signal) is perceived necessitates a detailed analysis of the cascade of events that transforms a chemical interaction into a neural code (Sharma et al., 2019). The process begins in the olfactory epithelium, located in the upper region of the nasal cavity, where millions of olfactory sensory neurons

(OSNs) extend their cilia into the nasal mucus. Odorant molecules bind to specific G protein-coupled receptors (GPCRs) located on the ciliary membrane. This binding initiates a well-defined transduction cascade: the activation of the GPCR induces a conformational change that activates the olfactory-specific G protein. The alpha subunit then stimulates type III adenylyl cyclase (ACIII), converting ATP into cyclic AMP (cAMP). The subsequent increase in cAMP causes the opening of cyclic nucleotide-gated (CNG) ion channels, allowing the influx of sodium and calcium ions. The resulting depolarisation is amplified by the calcium influx, which opens calcium-activated chloride channels, leading to chloride efflux and the generation of an action potential directed toward the olfactory bulb (Sharma et al., 2019).

In addition to classical olfactory receptors (ORs), the human epithelium expresses trace amine-associated receptors (TAARs), particularly TAAR5. These receptors are evolutionarily specialised to detect volatile amines present in bodily secretions, such as trimethylamine, and project to specific glomeruli with direct input to limbic areas, suggesting a conserved role in the detection of innate social signals (Maßberg and Hatt, 2018).

The axons of olfactory sensory neurons (OSNs) traverse the cribriform plate and terminate in the glomeruli of the olfactory bulb. Here, massive convergence occurs: thousands of neurons expressing the same receptor converge onto one or two glomeruli, creating a spatial odotopic map where chemical identity is encoded by the pattern of glomerular activation. Within the bulb, the information is processed by local circuits involving mitral cells, tufted cells, and inhibitory interneurons (granule and periglomerular cells), which refine the signal through lateral inhibition and synchronise neural activity into gamma and beta oscillations, both of which are essential for fine odour discrimination (Pause, 2012).

The main contribution of this paper is to propose a conceptual framework for integrating olfactory sensing into Human-Robot Teaming to enhance communication and collaboration. The paper highlights the potential of olfactory signals, which are integral to human emotional expression and communication, as a bio-inspired method for robots to interpret and respond to human emotional states. By incorporating olfactory sensors into robots, the paper suggests that robots can adapt their actions based on detected emotions, fostering more natural and empathetic interactions. Furthermore, the paper discusses the technical challenges, such as sensor development and data interpretation, and provides guidelines for future research directions, ensuring that ethical concerns are addressed in the integration of olfactory sensing into robotic systems. The ultimate aim is to create more intuitive, responsive, and collaborative human-robot interactions.

2 RELATED RESEARCH WORK

The “low road” enables a chemical stimulus to trigger an emotional or endocrine response, such as the activa-

tion of the stress axis, before the information undergoes cognitive processing. The medial amygdala serves as a critical hub for processing social and defensive signals, receiving direct monosynaptic input from the olfactory bulb (Mujica-Parodi et al., 2009). Simultaneously, the “high road” transmits signals to the piriform cortex and subsequently to the orbitofrontal cortex, where olfactory information is integrated with gustatory and visual inputs for hedonic evaluation and decision-making processes (Sharma et al., 2019). To understand how artificial intelligence can be trained to recognise an individual’s hormonal state, it is essential to analyse the chemical signature released. This does not involve directly detecting hormones in their gaseous phase, as molecules such as cortisol are poorly volatile. Instead, it requires identifying the complex bouquet of volatile organic compounds (VOCs) produced as a downstream effect of hormonal activation (Chang et al., 2024). In situations of stress, the body activates two main neuroendocrine axes: the sympathetic-adreno-medullary (SAM) axis releases catecholamines, specifically adrenaline and noradrenaline, triggering the immediate activation of apocrine sweat glands. On the other hand, the hypothalamic-pituitary-adrenal (HPA) axis leads to the release of cortisol. While cortisol itself is not volatile, its concentration strongly correlates with changes in the skin’s metabolic profile and the emission of specific volatile organic compounds (Zamkah et al., 2020). Emotional sweat is produced primarily by apocrine glands, particularly in the axillary region, unlike thermoregulatory eccrine sweat. Apocrine secretions are rich in odourless precursors—such as proteins, lipids, and steroids—which are converted into active chemosignals by the skin microbiome, especially by bacteria of the genera *Corynebacterium*, *Staphylococcus*, and *Micrococcus* (Van Herreweghen et al., 2020). Research has isolated several classes of molecules that collectively constitute the olfactory signature of stress. Branched carboxylic acids, such as (E)-3-methyl-2-hexenoic acid (3M2H), represent the primary component of male axillary odour, and their production increases significantly under adrenergic activation (Akutsu et al., 2006), while dodecanoic acid has also been identified as a marker of the sympathetic response (Gioia et al., 2022). Instead, androstadienol steroids, particularly androstadienone (4,16-androstadien-3-one), are detectable at close range and modulate cortisol levels as well as amygdala activation in women, effectively acting as a signal of male dominance or stress (Wyart et al., 2007). Additionally, isoprene, a highly volatile molecule, exhibits sharp spikes during episodes of acute anxiety, as demonstrated in environments like cinema ventilation ducts during scenes of intense emotional tension (Zaraska, 2025). Through GC-MS analysis, further specific markers have been identified, including elevated levels of benzoic acid, 2-methyloctadecane, and various xylene isomers in sweat induced by stress (Zamkah et al., 2020). Contrary to the historical emphasis on negative emotions, recent evidence demonstrates that joy can also be transmitted chemically. Exposure to what is known as “happiness

sweat” induces in recipients a simulacrum of the emotional state of the emitter, manifested through the contraction of the orbicularis oculi muscle, commonly associated with a Duchenne smile, as well as a more global perceptual attention. The chemical profiles of happiness tend to be richer in esters and cyclic molecules, unlike the sweat produced by fear, which is characterised by a higher abundance of aldehydes and ketones (Zaraska, 2025).

Affective Neuroendocrinology: Molecular Mechanisms of the Emotional Spectrum

Emotions are not fleeting events but rather physiological states orchestrated by neurotransmitters and hormones (Dfarhud et al., 2014). The Treatise on Affective Neuroendocrinology outlines the profiles associated with the fundamental emotional spectrum. Stress represents the physiological response to any threat to homeostasis, a process known as allostasis. The immediate reaction involves the amygdala activating the locus coeruleus and the lateral hypothalamus, thereby triggering the sympathetic-adreno-medullary (SAM) system. Adrenaline, acting as an “energy molecule”, increases heart rate and blood glucose levels. Simultaneously, the hypothalamic-pituitary-adrenal (HPA) axis is engaged, with the paraventricular nucleus releasing corticotropin-releasing hormone (CRH) and vasopressin (AVP), which stimulate the secretion of adrenocorticotrophic hormone (ACTH) from the pituitary gland. ACTH, in turn, prompts the release of cortisol from the adrenal cortex. In a healthy system, cortisol exerts negative feedback, inhibiting further CRH and ACTH release. However, dysregulation of this process leads to “allostatic load” which can result in hippocampal atrophy and hypertension (Miller and O’Callaghan, 2002). Joy is a composite construct that can be divided into three interconnected components. First, desire, or wanting, is mediated by the dopaminergic system of the ventral tegmental area (VTA) and substantia nigra. Dopamine operates according to the Reward Prediction Error (RPE) principle, signaling salient stimuli and driving motivational behaviour. Second, hedonic pleasure, or liking, is mediated by endogenous opioids, such as endorphins, and endocannabinoids, like anandamide, which act within brain regions known as “hedonic hotspots” generating the subjective experience of pleasure. Finally, satisfaction, or satiety, is supported by serotonin and oxytocin, which promote emotional stability and social bonding, contributing to a sense of fulfilment and contentment (DSOUZA et al., 2020). Sadness is characterised by a reduction in monoamine levels and alterations in the opioid system. Panksepp’s Opioid Withdrawal Theory posits that social separation induces a neurochemical state akin to narcotic withdrawal. Emotional tears, for instance, contain elevated concentrations of adrenocorticotrophic hormone (ACTH), prolactin, and leucine-enkephalin, reflecting the body’s physiological response to distress (Lumley et al., 2011). Disgust, an evolutionarily ancient emotion, functions as a form of “behavioural immune system”. Approximately 95 percent of the body’s serotonin is located in the gut, and

the detection of toxins activates 5-HT₃ receptors on the vagus nerve, triggering nausea. Vasopressin levels surge dramatically during nausea, even before conscious symptoms emerge. Social pain exhibits a profound overlap with physical pain. Social rejection activates the dorsal anterior cingulate cortex (dACC) and the anterior insula, the same brain regions that encode the affective component of physical pain. Substance P (SP) mediates both nociception and emotional discomfort in limbic areas, underscoring the shared neurobiological basis of these experiences (Lumley et al., 2011).

Brain Processing In the Recipient and Emotional Contagion

When volatile stress molecules reach the recipient, they trigger a neurobiological sequence distinct from the perception of neutral odours (Mujica-Parodi et al., 2009). Functional MRI studies have shown that inhaling stress-induced sweat robustly activates the amygdala in the recipient, even when the odour is not consciously perceived (Mujica-Parodi et al., 2009). Androstadienone sustains elevated cortisol levels in women and activates the ventromedial hypothalamus. This creates an interpersonal chemical feedback loop: the emitter’s stress generates a volatile signal that raises cortisol in the recipient, thereby preparing the group to respond to potential threats (Wyart et al., 2007). The perception of chemosignals recruits brain regions that overlap with the mirror neuron system (MNS), inducing an embodied simulation of another individual’s emotional state. In the presence of fear-related odours, connectivity between the piriform cortex and the amygdala intensifies, lowering the response threshold to visual threat stimuli. This heightened neural interaction enables the brain to detect frightened faces more rapidly, thereby enhancing collective vigilance (Brasi and Seccomandi, 2025).

3 MACHINE OLFACTION

To artificially replicate these capabilities and achieve synthetic olfactory sensing, often termed machine olfaction, a hybrid approach is required, integrating various sensing technologies capable of detecting traces at parts per billion (ppb) concentrations. Electronic noses (E-Noses) for volatile organic compounds (VOCs) employ metal oxide sensors (MOS), which measure changes in conductivity caused by gas adsorption. While widely used, these sensors are prone to temporal drift and humidity sensitivity (Chang et al., 2024). Conductive polymer sensors and nanocomposites, on the other hand, provide greater selectivity for specific organic molecules, and the use of functionalised graphene or carbon nanotubes is enhancing sensitivity to volatile biomarkers. Quartz crystal microbalance (QCM) sensors are particularly useful for detecting heavier compounds, such as steroids, by measuring mass variations on the crystal surface (Torrente-Rodríguez et al., 2020). For cortisol, the direct marker of stress, its low volatility makes gaseous detection challenging. The

most effective strategy involves interfacing artificial intelligence with wearable biosensors that utilise molecularly imprinted polymers (MIPs) or aptamers immobilised on flexible electrodes (Tang and He, 2024). These wearables enable highly specific, non-invasive, real-time monitoring of cortisol in liquid sweat. Recent research is also exploring the possibility of detecting cortisol-containing aerosols in condensed breath using microfluidic systems coupled with ultra-sensitive electrochemical sensors (Batoool et al., 2026).

AI Training: Protocols and Algorithms

To build a model capable of recognising olfactory stress, a rigorous pipeline based on physiologically validated data is essential. Training must rely not on subjective questionnaires but on a biological “ground truth”. Standardised stress induction is achieved through the Trier Social Stress Test (TSST), while biochemical validation ensures that only samples with confirmed elevated salivary cortisol levels are labelled as “stress” (Preti et al., 2019). Reference chemical analysis, conducted using gas chromatography-mass spectrometry (GC-MS), identifies the molecular features (such as peaks of 3M2H or dodecanoic acid) that the electronic nose (E-Nose) must learn to recognise (Zamkah et al., 2020). The raw sensor data consists of high-dimensional, noisy time series, which require preprocessing algorithms to correct for drift and thermal normalisation (Cai et al., 2024). A one-dimensional convolutional neural network (1D-CNN) extracts local morphological features from the sensor time series, while long short-term memory networks (LSTMs) are crucial for managing temporal dependencies and distinguishing transient peaks from sustained changes in odour emission (Voss et al., 2014). Graph neural networks (GNNs) represent the most advanced frontier in this field. Instead of relying on predefined chemical descriptors, GNNs (such as message-passing neural networks (MPNNs)) learn directly from molecular structures represented as graphs (Grodniyomchai et al., 2019). The Osmo project, led by Alex Wiltschko, utilised GNNs to create a “Principal Odour Map” (POM), a digital map that preserves human perceptual relationships, such as floral hierarchies, more effectively than expert human panels (Lee et al., 2023). This approach enables the “digitisation” of odours by mapping chemical structures directly to olfactory perception, analogous to how wavelengths map to colour in vision (Lee et al., 2023). Superior performance is achieved by combining electronic nose (E-Nose) data with physiological signals, such as heart rate variability (HRV) and electrodermal activity (EDA), as well as visual inputs. Architectures like Emotion-LLaMA integrate audio, video, and text through domain specific encoders, aligning features in a shared semantic space to enhance the accuracy of emotional reasoning (Cheng et al., 2024). Fusing volatilome data with facial micro-expressions enables systems to overcome the limitations of unimodal approaches, which are often vulnerable to environmental noise (Almulla, 2024).

4 VOLATILOME, PATHOLOGY, AND ENVIRONMENTAL WELLBEING

The analysis of human and environmental volatilomes holds profound implications for early diagnostics and public health (Palmisani et al., 2025). Data from the National Health and Nutrition Examination Survey (NHANES) have revealed significant associations between exposure to specific volatile organic compounds (VOCs) and the prevalence of depressive disorders (Zhuang et al., 2023). Additionally, research has demonstrated that humans can detect olfactory signals of immune activation just a few hours after exposure to a pathogen, such as lipopolysaccharide (LPS) induction (Regenbogen et al., 2017). Sweat from individuals experiencing an active immune response is perceived as less pleasant, triggering social avoidance mediated by the orbitofrontal cortex and the superior temporal sulcus, a mechanism evolved to reduce disease transmission (Cepon-Robins et al., 2021). In contrast to stress-related VOCs, compounds emitted by plants, such as biogenic VOCs like pinene and limonene, have shown anti-inflammatory and antioxidant effects on the airways (Antonelli et al., 2020). Inhaling these terpenes enhances parasympathetic nervous system activity and increases the amplitude of alpha waves in electroencephalography (EEG), inducing a state of physiological relaxation while improving cognitive function and mood (Kay et al., 2025).

5 TECHNOLOGICAL CHALLENGES AND ETHICAL BARRIERS

Despite significant advancements, a substantial gap remains between biological and artificial olfactory systems. The human olfactory system features approximately 400 different types of receptors and a unique regenerative capacity. In contrast, metal oxide sensors (MOS) often lack the sensitivity required to detect femtomolar traces of certain steroids. Furthermore, the high individual variability in microbiome composition and odour profiles, shaped by diet, major histocompatibility complex (MHC) genetics, and hygiene, poses a considerable challenge for the generalisation of artificial intelligence models (de Groot et al., 2020). For instance, a polymorphism in the ABCC11 gene results in marked differences in axillary odour production between populations of Asian and European descent, necessitating representative training datasets and debiasing techniques to prevent diagnostic errors. The ability of machines to detect invisible internal states also raises urgent ethical concerns. The chemical signature unknowingly emitted by an individual could be exploited for non-consensual surveillance or aggressive commercial profiling. It is imperative to establish regulatory frameworks that safeguard the integrity of the volatilome as sensitive data, preventing the misuse of technologies capable of “reading” our most intimate emotions through the air (Mershin et al., 2025).

6 CONCLUSION AND FUTURE WORK

The integration of olfactory neurobiology with artificial intelligence is opening new possibilities in the field of Human-Robot Teaming (HRT), where robots are not only data analysers but also empathetic collaborators. The recognition that emotions have a molecular basis, encoded in chemical signals decoded by the brain prior to conscious awareness, transforms artificial intelligence from simple processing systems to more intuitive and emotionally responsive entities.

Wearable devices, such as those based on aptamer-field-effect transistors (FETs), are paving the way for continuous monitoring of hormonal biorhythms. These technologies could enable the personalised management of conditions like anxiety, depression, and Cushing's syndrome, offering a more tailored approach to healthcare. In addition, olfactory sensors calibrated to detect stress-related volatile organic compounds (VOCs) could be deployed in critical environments, such as airports or stadiums, to identify agitated individuals. When integrated with artificial vision systems, this approach could enhance security measures by providing more accurate, non-invasive methods for threat detection.

In the context of social and collaborative robotics, the use of olfactory signals, such as estratetraenol, could influence human trust and cooperation, effectively reducing psychological barriers in Human-Robot Teaming (HRT). This ability for robots to perceive and adapt to human emotions could improve collaboration and task performance in various settings. On a broader scale, Aroma Intelligence Systems (AIS) that analyse VOCs could enable the creation of planetary wellbeing metrics, helping monitor ecosystem health and assess the biosphere's response to climate change.

Ultimately, the integration of affective neuroendocrinology with olfactory artificial intelligence provides a holistic view of humans as interconnected systems where every emotion is linked to a specific chemical signal. The transition from simple gas detection to the recognition of complex emotional patterns marks the beginning of a new era in which robots, as part of Human-Robot Teaming (HRT), will not only see and hear but also "understand" the biological essence of human emotion. This advancement has the potential to significantly improve the empathy, adaptability, and responsiveness of robots in collaborative environments, fostering more effective and emotionally intelligent human-robot interactions.

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