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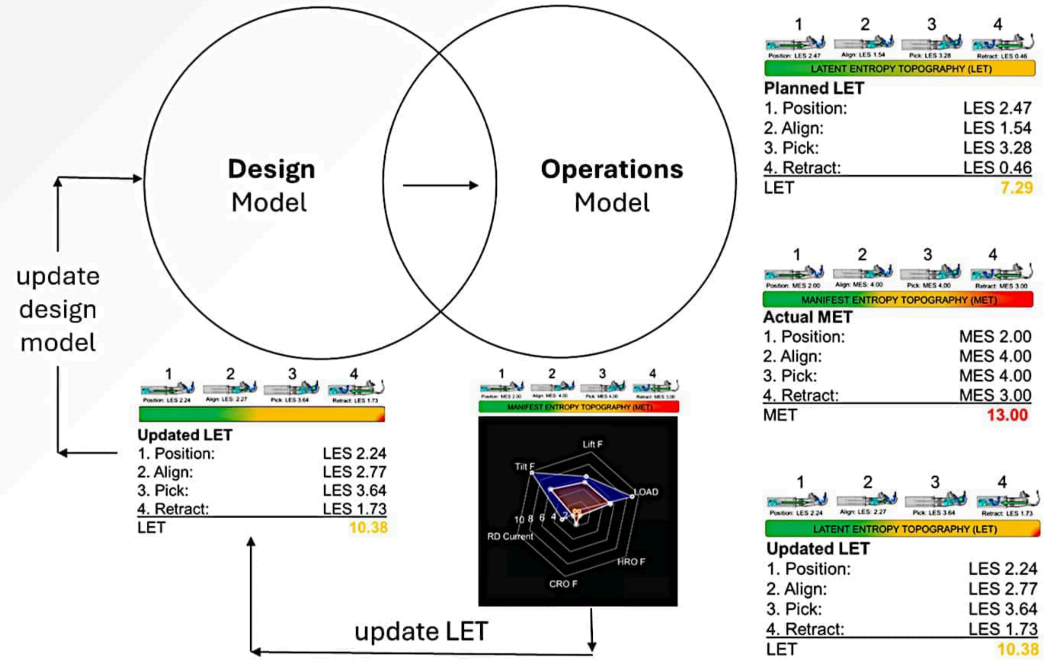

Extreme fitness: Applying ecophysics to reduce human stress in everyday extreme environments

Stephen Fox | Janne Lyytinen | Hannu Saarinen

VTT TECHNOLOGY 445

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Stephen Fox

VTT Technical Research Centre of Finland Ltd

Janne Lyytinen

VTT Technical Research Centre of Finland Ltd

Hannu Saarinen

VTT Technical Research Centre of Finland Ltd

ISBN 978-951-38-8809-1

VTT Technology 445

ISSN-L 2242-1211
ISSN 2242-122X (Online)
DOI: 10.32040/2242-122X.2026.T445

JULKAISIJA – PUBLISHER

VTT
PL 1000
02044 VTT
Puh. 020 722 111
https://www.vtt.fi

VTT
P.O. Box 1000
FI-02044 VTT, Finland
Tel. +358 20 722 111
https://www.vttresearch.com

Preface

It has been proposed that ergonomics and human factors (EHF) can be advanced by moving beyond old methodologies, by strengthening theoretical basis, and by making more use of artificial intelligence. Here, with the example of human remote operation of robots, i.e., teleoperation, it is argued that progress towards realising proposals for advancing EHF can be made by increasing reference to ecophysics. That is by increasing reference to science concerned with interactions between ecological systems and physical laws. In this document, human stress associated with remote operations work is situated in the broader context of extreme work environments. Those being environments that many people experience every workday, such as typical factories and offices, which are far from the natural environments in which humans evolved. With reference to ecological fitness, morphological fitness, and tripartite entropy, it is explained how application of ecophysics in EHF has potential to reduce human work stress.

Contents

1 Introduction

Ecophysics is concerned with interactions between ecological systems and physical laws [1,2,3]. In this paper it is argued that building on ecophysics can contribute to realising proposals to advance ergonomics and human factors (EHF) [4]. In particular, contribute to moving beyond old methodologies, strengthening theoretical basis, and making more use of artificial intelligence [4]. Focusing on the established EHF topic of improving the performance of human remote operation of robots [5], i.e., improving teleoperation [6], examples of how these proposals can be realised by building on ecophysics are explained in the remaining four sections of this document. In the next section, an example is provided of moving beyond old methodologies to new methodologies that can facilitate the development of new solutions. This example is moving beyond socio-technical systems to biosocial-technical systems [7]. In the third section, an example is provided of strengthening theoretical basis. This example is based on interactions between ecological fitness [8] and psychological entropy [9] in learned helplessness that can arise from work stress [10]. In the fourth section, an example is provided of how artificial intelligence can be harnessed in hybrid intelligence systems [11]. This example is design for safe automation [12] based on latent and manifest [13] tripartite entropy [14] in morphological fitness [15]. All the examples relate workplace stress to extreme environments. Those being typical modern work environments, such as typical factories and offices, which are far from the natural environments in which humans evolved [16,17,18,19]. In conclusion, principal contributions are stated, future research directions are proposed, and practical implications are discussed. The overall contribution is to argue that increased reference to ecophysics has potential to advance EHF for remote operations specifically and to advance EHF generally.

2 Moving beyond old methodologies

It has been argued that EHF is stuck in the past [4]. An example is locked-in [20] path dependent [21] fixation [22] on socio-technical systems thinking that began in the middle of the last century [23]. For example, in 2025 it has been argued that socio-technical systems (STS) can be leveraged to tackle grand challenges including human-robot teams [24]. However, STS is a limiting framing because it does not encompass individual people's biology in psychophysiological psychomotor functioning when interacting with robotics [25]. This is one example of why it is necessary to move beyond STS to biosocial-technical systems (BSTS) [7,26,27,28].

An example of not integrating BSTS in EHF is the introduction of automated monitoring of people [29] such as people who perform remote operation of robotics [30]. This is done despite remote operation work already being stressful [31,32] and automated monitoring increasing stress [33,34]. Rather than persist with this negative course of action, BSTS opens potential to refer to ecophysics to develop new solutions that directly address sources of stress in remote operation of robots. In doing so, reference can be made to the ecophysics of biological fitness at the ecological level [8] and at the morphological level [15].

Ecological fitness refers to the fit of species with the environments in which they seek to survive [8]. As summarized by the phrase, survival of the fittest [35], if ecological fitness increases, then there can be increased potential for survival. Hence, species evolve ecological fitness functions to be able to solve survival problems in environments [36,37]. However, ecological fitness functions evolved over millennia may suddenly stop solving survival problems when human ecosystem engineering [38] leads to human-induced rapid environmental change [39]. For example, the ecological fitness of people who have survived for millennia throughout the world by doing work that required gross motor strength is radically reduced by industrial automation that is concentrated in just a few countries [40].

Even if office buildings are available as an alternative environment in which to try to do work to survive, office work can entail such negative effects on functions evolved in natural environments that some people can become incapable of doing any work [18]. Furthermore, in addition to tangible physical changes to the environment, such as the construction of factories and offices, there can be more intangible changes such as competition in many types of work changing from being local to being global [19]. Human work that is already stressful in typical modern work settings can be even more stressful when people's work involves remotely operating work being done by robots in other environments [31,32]. Tangible ecological pressures and intangible ecological pressures can contribute to humans suffering from learned helplessness [41,42,43]. Learned helplessness involves unlearning that it can be possible to have some control over environmental stressors [44] and is associated with a wide range of negative effects [45,46]. Yet, despite its significance, learned helplessness has received little consideration within EHF. Rather, EHF continues to be more focused on traditional EHF topics such as musculoskeletal disorders [47,48].

Hitherto, there has been limited consideration of ecology in EHF. For example, there has been some consideration of the ecological affordances in the workplace [49], and interface design that is focused upon workplace equipment and environments, rather than focused on users, has been called ecological interface design [50]. Although there has been little consideration of ecology in EHF, fit is a fundamental construct in EHF: for example, fitting work tasks to people and fitting people to workplaces [51,52]. Yet, there has been little consideration of ecological fitness [8] and related constructs such as ecological traps [53] and sensory ecologies [54] in EHF. An initial step towards addressing lack of consideration of ecological fitness in EHF is explained in the third section of this document.

Furthermore, although the word morphology has been in used in EHF in relation to body morphology [55,56], there has been little, if any, consideration of morphological ecology and fitness [15,57,58] in EHF. Morphological ecology encompasses how form and function evolve through adaptation in an environment to increase ecological fitness in that environment [57,58]. When there is complete morphological fitness there will be no information uncertainty about how to do the work needed to survive in an environment, because form and function have adapted to completely fit the work to be done. When there is complete morphological fitness work can be done correctly first time and there are minimal actions to be performed. By contrast, the lower the fit between the work to be done and form/function, the higher will be the average number of attempts that will be needed to complete work. The higher the average number of attempts, the higher will be the tripartite entropy of information uncertainty leading to physical disorder that entails energy loss (i.e., information-theoretic entropy leading to statistical physics entropy that entails thermodynamic entropy) [14,59]. The more complete the morphological fitness of robots, the less need there will be for stressful remote operation of robots by people. This because where there is complete robot morphological fitness, there can be full automation of robot operations. Accordingly, as explained in the fourth section of this document, an alternative to increasing the work stress of human remote operators by continual monitoring [33,34] is to develop solutions that reduce the tripartite entropy involved in the work being done by robots.

3 Strengthening theoretical basis

Figure 1 below provides a summary of a preliminary theoretical framework of decreasing ecological fitness [8] and increasing learned helplessness [10], which can be referred to when assessing potential for psychological entropy in workplaces [9]. The preliminary framework is explained in the following paragraphs.

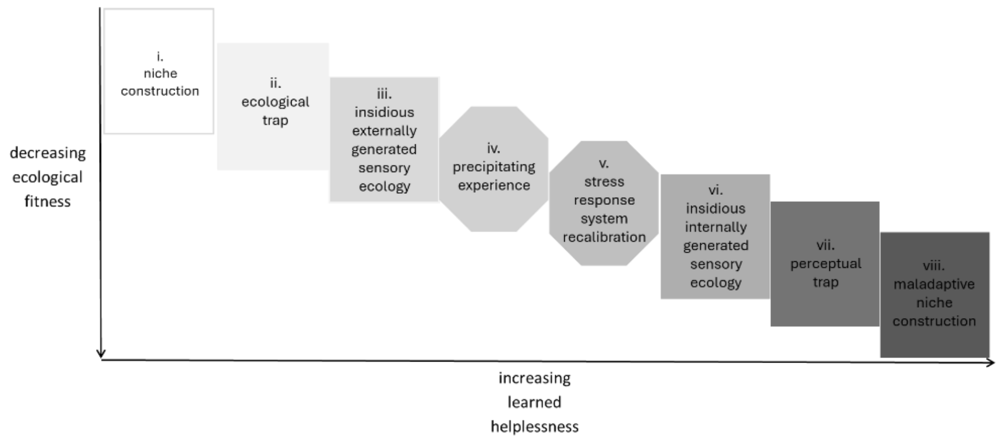


Figure 1. Decreasing ecological fitness and increasing learned helplessness

Human niche construction (i) involves human modification of environment that is both material and social [60]. For example, a company can modify environments by constructing comfortable work buildings that have comfortable work equipment and a comfortable work culture. However, this can lead to ecological traps (ii) [53] in which people prefer habitats where their ecological fitness is lower than in other available options. This can happen after historically reliable relationships between environmental cues and environment quality have been changed by human-induced rapid environmental change [39]. For example, doing physically light work while sitting on a comfortable chair inside a comfortable air-conditioned building can entail more immediately pleasing environmental cues than those experienced when hunting and gathering outside in all weathers. However, human fitness functions evolved for hunting and gathering, and hunter-gatherer populations are remarkable for their excellent health [61].

Sensory ecology (iii) involves seeking to optimise the acquisition of information from the environment in which survival is intended. In particular, optimising the trade-off between costs of making wrong choices due to lack of relevant information versus the energy/time/risk costs involved in acquiring relevant information [54]. When historically reliable relationships between environmental cues and environment quality have been changed by human-induced rapid environmental change [39], the optimal sensory ecology trade-off can be distorted. For example, distorted by multiple environmental cues of comfort belying the potential for stress from sitting in a comfortable chair when doing physically light work inside a comfortable building [62]. The sensory ecology in such situations can be described as an insidious externally generated sensory ecology because environmental cues are generated by the world rather than by the person [63], and their harmfulness is not apparent in the short-term within an ecological trap in which life is relatively comfortable but nonetheless can entail increasing stress [64,65]. Thus, extreme work environments can encompass work environments that are extremely comfortable.

Stress can predispose people to functional disorders [66,67]. Then, functional disorders may be precipitated by a minor experience [68]. Precipitating experiences (iv) can include events from which a quick recovery would be expected, such as a migraine or a minor physical injury. However, rather than a quick recovery, symptoms can be perpetuated, for example, by anxiety [69]. Anxiety can increase if a person becomes hypervigilant to their environment and narrows attention to stimuli associated with threat [70]. This can be more likely if there is recalibration of the stress response system (v) as people try to survive in changed circumstances [71]. For example, subsequent to a precipitating experience, people's attention can be directed towards potential triggers of their ongoing functional disorders [72].

This can contribute to sensory ecology shifting from being less externally generated to being more internally generated (vi). This can happen through what is described as predictive processing [73], and expectations of pain leading to experiences of pain [74]. Such sensory ecologies can be described as insidious internally generated sensory ecologies because their harmfulness is not apparent in the short-term. However, from an ecological perspective, they could lead to perceptual traps (vii) within which people avoid high quality habitats [75]. For example, people can seek to avoid any environment in which physical activity will be needed [76].

Accordingly, people may engage in maladaptive niche construction (viii) by modifying their environment to minimize the extent to which they need to move [77]. Maladaptive niche construction can be considered to be an attempt to reduce psychological entropy [9,78]. This can involve attempting to reduce anxiety arising from increased uncertainty by managing opportunities for action in the environment, i.e., by managing affordances [9]. However, although maladaptive niche construction could reduce helplessness in a small part of the environment, for example adapting a room in a home to reduce the amount of movement needed, this could inadvertently increase learned helplessness by leading to reduced ecological fitness with all other environments outside of the small part of the environment within the scope of the maladaptive niche construction.

Development of interventions to reduce learned helplessness is an ongoing field of research [79,80]. Meanwhile, there is some evidence that fostering growth mindsets and psychological flexibility could be beneficial [81,82]. From the perspective of strengthening theoretical basis of EHF, the preliminary framework summarized in Figure 1 could provide a starting point for development of a classification structure to inform assessment of which types of EHF actions can be most effective at which stages to address decreasing ecological fitness. It is important to note that many existing work environments that have been carefully designed using established EHF methods may be ecological traps. For example, work environments that have been carefully designed for human remote operators of robots can be ecological traps within which work stress [31,32] can be increased by automated monitoring of human remote operators [33,34]. Thus, human remote operators could already be at Figure 1iv or Figure 1v on the way to learned helplessness. Hence, rather expanding automated monitoring of people who do remote operation work, it is important to develop new solutions that directly address sources of stress in remote operation of robots. An example of how this can be done is provided in the next section.

4 Harnessing artificial intelligence

It has been argued that EHF needs to make more use of artificial intelligence (AI), and there should be use of AI for design [4]. Accordingly, the example provided here for harnessing artificial intelligence is design for safe automation. This example is also aligned with another requirement for advancing EHF: to focus more on real-world necessity [4]. With regard to AI there is real-world necessity to address the inaccuracy of outputs from Generative AI (GenAI) [83,84,85]. Moreover, there is real-world necessity to address the increasing unsustainability of GenAI as they entail vast energy expenditure and enormous water consumption [86,87,88].

In terms of sensory ecology, GenAI is very far from optimising the trade-off between the costs of making wrong choices in an environment due to lack of relevant information about the environment versus the energy/time/risk costs involved in acquiring relevant information about the environment [54]. On one side of the trade-off, it is widely reported that use of GenAI can facilitate making wrong choices [83,84,85]. On the other side of the trade-off there is vast energy expenditure [86,87,88] and risks arising from inherent characteristics of AI models such as drift and degradation [89,90,91]. As a consequence of inaccuracy risks, any initial reductions in time brought by GenAI can be off-set by the time that people have to spend checking GenAI outputs. Alternatively, if people do not spend time carefully checking GenAI outputs, then there can be time to be spent later in addressing negative consequence from not carefully checking GenAI outputs earlier [83,84,85].

In stark contrast to the operation of GenAI, survival is facilitated by productively expending the minimum amount of energy possible in advance to prevent unproductive energy expenditure in the future that can arise from information uncertainty that entails physical disorder. An everyday example is expending a little energy in advance by fixing a key rack to a wall close to a door to prevent not knowing where door keys are in the future, and so prevent future physical disorder and unproductive energy expenditure that would be involved in looking for lost door keys. Fixing a key rack to a wall is an example of expending the minimum amount of energy in advance to be able to locally resist the universal tendency towards maximum entropy [92,93]. The better the fit with an environment, the less energy needs to be expended in advance to resist entropy in the future. This is because the higher the fit with an environment, the lower is the information uncertainty, physical disorder and energy loss (i.e., tripartite entropy) in work done to survive in that environment. When there is complete fitness, there can be minimum redundant variation and least action in doing work needed to survive. By contrast, GenAI are very far from alignment with the fundamentals of ecophysics upon which depends survival in changing environments. In particular, GenAI are far from dimensional reduction [94,95] and far from the principal of least action [96,97]. Rather, GenAI can have billions of parameters and expend vast amounts of energy in computations [86,87,88], which can lead to people having to do more work themselves [83,84,85]. Thus, what is revolutionary about GenAI is that they work in opposition to the fundamentals of ecophysics upon which survival depends as they generate inaccurate information [83,84,85] while they expend vast amounts of energy and consume enormous amounts of water [86,87,88].

Accordingly, rather than applying GenAI, EHF should seek to harness AI by making targeted selective frugal use [98], i.e., thrifty use [99], of artificial intelligence that can be developed in congruence with the fundamentals of ecophysics upon which survival depends. Here, physics-informed machine learning has some relevance [100]. However, machine learning models that are intended to incorporate physics [101] are not consistent with the fundamentals of ecophysics if they are large models that are not consistent with nature being thrifty in all its actions [102] through evolution towards dimensional reduction [94,95] and least action [96,97]. Accordingly, there is need and opportunity to address another requirement for advancing EHF: to engage in serious innovation [4].

Figures 2 to 5 below summarize an example of applying the ecophysics of morphological fitness to the human remote operation of a semi-autonomous robot (SAR) that is designed to be used to change components inside a nuclear fusion reactor [103]. This is an example of design for safe automation of robotics, which is intended to minimise latent tripartite entropy that could become manifest tripartite entropy during the changing of components. This example is aligned with safety science based on "improving safety in a complex system can be seen as a fight to reduce entropy" [104]. In Figure 2, an overview of a remote operation task is shown.

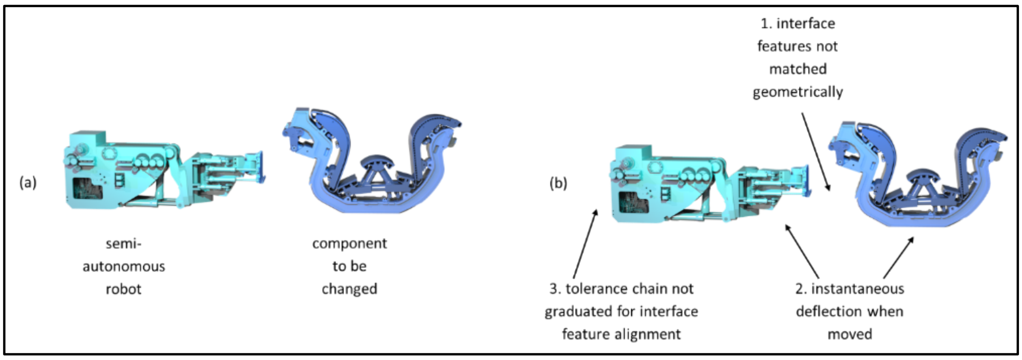
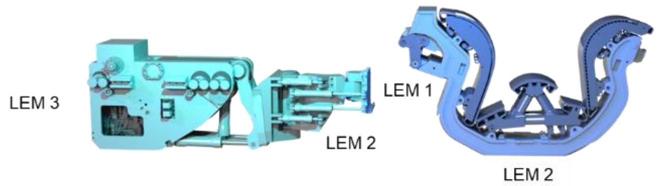


Figure 2. Remote operation task. (a) robot and component. (b) sources of entropy.

In Figure 2a, a semi-autonomous robot and a component to be changed by the semi-autonomous robot (SAR) are shown. In Figure 2b, three sources of entropy are shown. The first source is that interface features of the SAR and the component are not matched geometrically. The second source is that both the SAR and the component can suffer from instantaneous deflection when moved. The third source is that the tolerance chain for the movement of the SAR is not graduated for alignment of the interface. In other words, there is a breadth of tolerance that is appropriate for the SAR moving close to the component, but that breadth of tolerance is too wide for connecting the SAR to the component to be changed. These three sources of entropy arise from a lack of critical morphological fitness between the semi-autonomous robot and the component to be changed.

Critical morphological fitness refers to morphological fitness that is critical to successful performance of work that needs to be done to survive. Consider, for example, if a field robot that needs to descend a slippery icy hill has smooth outward morphology and internally the field robot morphology does not include a transmission system that has a hill descent gear, then the field robot will not be able to descend the hill safely. Rather, the field robot may crash and not be able to perform work. By contrast, if a field robot that needs to descend a slippery icy hill has non-slip outward morphology and internally the field robot morphology includes a transmission system that has a hill descent gear, then the field robot can descend the slippery icy hill safely with least action at the first attempt. There may be many other features of the field robot's outward morphology and internal morphology but none of them are critical to safely descending the slippery icy hill.

Returning to the example summarized in Figure 2, Figure 3 below provides an example of calculations of latent entropy arising from the three sources, which are labelled as latent entropy marker (LEM) 1, LEM 2, and LEM 3.



Latent Entropy Markers (LEM)	unequal discrete probability distribution of number of attempts to complete tasks	information -theoretic entropy	average number of attempts to complete task
LEM 1: interface feature mismatch	(0.4, 0.4, 0.2)	1.52	2.87
LEM 2: instantaneous deflection	(0.6, 0.2, 0.2)	1.37	2.58
LEM 2: instantaneous deflection	(0.6, 0.2, 0.2)	1.37	2.58
LEM 3: ungradated tolerance chain	(0.3, 0.3, 0.3, 0.1)	1.90	3.73

Latent Entropy Signature (LES) (2.87 + 2.58 + 2.58 + 3.73) = **11.76**

Figure 3. Calculation of a latent entropy signature

Detailed explanation for the calculations is provided in [59]. In Figure 3, it is shown that only because of the interface feature mismatch, LEM 1, the average number of attempts needed for the SAR to connect to the component would be 2.87. This average number of attempts is calculated by first defining the number of different ways that the SAR could connect to the component. If there was complete morphological fitness, then there would be only one way that the SAR could connect to the component in what would be a perfect fit that would be completed correctly every time. However, just for LEM 1 there can be three different ways that the SAR could connect to the component. In every ten attempts, the probable distribution of how the SAR would connect to the component would be for LEM 1.1 four attempts (i.e., 0.4), for LEM 1.2 four attempts (i.e., 0.4) and for LEM 1.3. two attempts (i.e., 0.2). This unequal discrete probability distribution of number of attempts to complete the task (0.4,0.4,0.2) can be expressed as an information-theoretic entropy of 1.52, which corresponds to an average number of attempts to connect the SAR to the component of 2.87. In Figure 3, the average number of attempts related to each source (i.e., to each LEM) is calculated separately and then added together to provide a latent entropy signature (LES) of 11.76 for the operation of the SAR connecting to the component.

Separate calculation of each LEM can inform design for safe automation by informing design refinement of specific design features individually. For example, redesign to reduce LEM 2, i.e., to reduce deflection. However, in practice, the different sources would not have independent effects, and their joint effects can be calculated in terms of joint entropy. Calculation of joint entropy will reveal that the combination of LEMs will lead to a much higher LES. Calculation of joint entropy can highlight that redesign is imperative to reduce the stress that can be experienced by a human remote operator who is expected to perform operations correctly at the first attempt but who has to work with a design that entails that there are many different ways in which there can be interaction between the SAR and the component. Details of how different types of entropy, including joint entropy, can be calculated in relation to different types of work are provided in [105].

The calculation of entropy from probability distributions is straightforward when using free-of-charge online entropy calculators and need not involve application of artificial intelligence. By contrast, the definition of how many different ways an operation could be done and the probability distribution across the different ways could be improved through thrifty application of AI. This can be done through application of established computational simulation and analysis methods that are already used in three-dimensional (3D) digital design modelling, such as clash detection [106], collision detection [107], gravity analysis [108], interference detection [109], path planning [110], position and orientation best-fitting [111], and assessment of maintainability [112]. Organisations that offer design simulation and analysis tools gradually introduce AI into their offerings if doing so can improve their performance [113,114]. Figure 4 below provides an illustration of how LES for tasks can be added together to provide a latent entropy topography (LET) for a sequence of tasks.

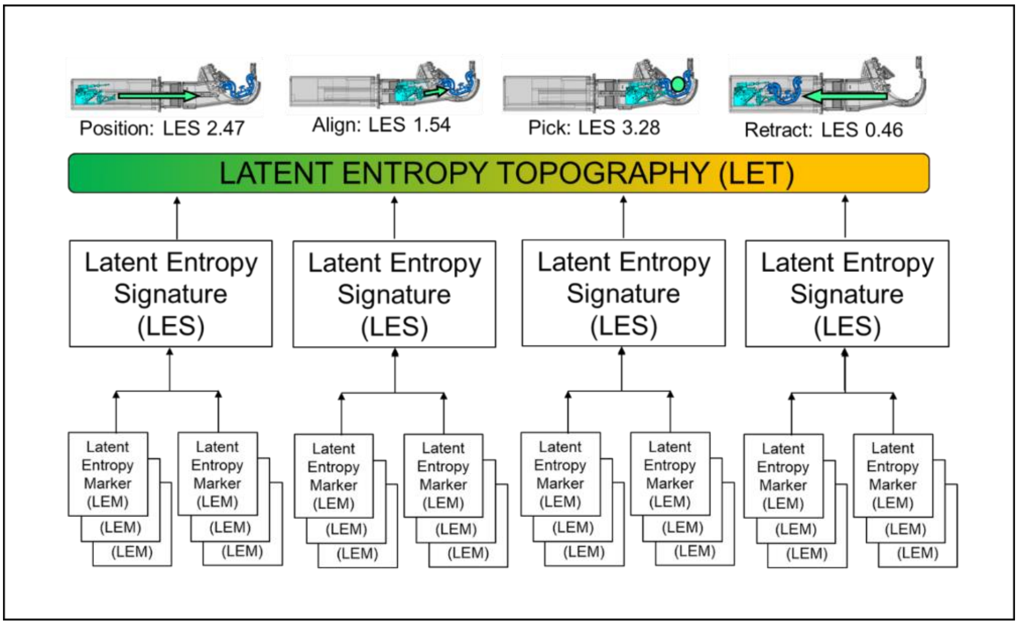


Figure 4. A latent entropy topography

In this example, the tasks are positioning the SAR, aligning the SAR, the SAR picking up the component, and the SAR retracting the component. As illustrated in Figure 4 and Figure 5, the increasing entropy from the accumulation of LES in the LET can be related to the potential for human remote operators experiencing stress with typical traffic light colours: green, amber, red.

Figure 5 below provides a summary of morphological adaptation to increase the morphological fitness of remote operations work. The diagram in Figure 5a shows a summary of a remote operator stress management method based on morphological adaption to increase morphological fitness. Figure 5b shows the planned LET, the actual manifest entropy topology (MET), and the updated LET based on feedback during the remote operation of the SAR. Detailed explanation of interplay between latent entropy and manifest entropy is provided in [13,14]. The radar chart within Figure 5a can be used by the remote operator to get a real-time visual summary of the SAR's movements.

With the method summarized in Figure 3 to 5, there is morphological adaption to increase morphological fitness during the design phase through iterations of design and entropy measurement. Then, there is further morphological adaption based on feedback from actual remote operations that include measurement of MET and further redesign to update LET. With regard to artificial intelligence, such practice is consistent with human-in-the-loop AI techniques such as machine teaching [115]. This ecophysics-based approach is opposite to established approaches that do not directly address sources of stress in the work to be done, but instead can increase the amount of stress that is experienced in doing work [33,34].

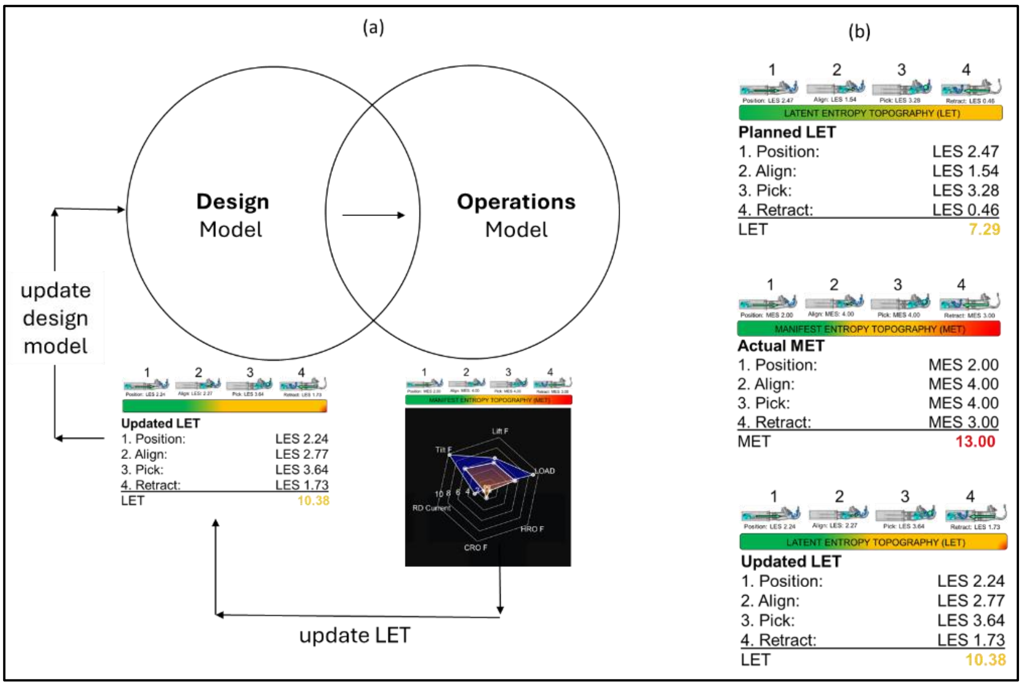


Figure 5. Morphological adaptation to increase morphological fitness. (a) Remote operator stress management method. (b) Adaptation measured in latent entropy and manifest entropy.

5 Conclusions

In 1995, there was a call for EHF to address the coming global problems of the twenty-first century [116]. Three decades later, rather than EHF having made important contributions to addressing global problems, it has been argued that EHF is fading away [4]. In this paper, with the established EHF topic of human remote operation of robots, i.e., teleoperation, three interrelated examples have been provided to illustrate how proposals to improve EHF [4] can be fulfilled through reference to ecophysics. These examples have encompassed moving beyond old methodologies; strengthening theoretical basis; and harnessing artificial intelligence. Together, the three interrelated examples illustrate that increased reference to ecophysics has potential to advance EHF research and practice.

Reference to ecophysics can yield many potential directions for future EHF research. One potential direction is to reassess working environments that have been developed with established EHF in order to determine to what extent, if any, they are ecological traps. This could include reassessing working practices that have been developed with established EHF in order to determine to what extent, if any, they entail an insidious externally generated sensory ecologies. Subsequently, reference to ecophysics could inform the development of new knowledge to guide redesign of working environments and working practices in order to reduce sources of work stress that could predispose people to becoming vulnerable to functional disorders and learned helplessness.

Reference to ecophysics can also provide many potential directions for improving EHF practice. One major practical direction can be increasing the personalisation of solutions that are informed by EHF. For example, the relating of LET and MET to green-amber-red shown in Figure 5 can be personalised for each person by each person relating LET and MET to the extent of the stress that they experience personally. Overall, EHF can contribute to personalisation of working practices by moving beyond the socio-technical systems perspective, which is focused on interactions between social groups and technologies, to biosocial-technical systems perspectives that encompass the psychophysiological psychomotor biology of individuals. In doing so, it is important to recognise that many everyday working environments can be extreme environments for us because they are far from the natural environments in which we evolved ecological fitness.

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Series title and number

VTT Technology 445

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Author(s)	Stephen Fox, Janne Lyytinen, Hannu Saarinen
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ISBN, ISSN, URN	ISBN 978-951-38-8809-1 ISSN-L 2242-1211 ISSN 2242-122X (Online) DOI: 10.32040/2242-122X.2026.T445
Date	February 2026
Language	English
Pages	22 p. + app. 0 p.
Name of the project	
Commissioned by	
Keywords	biosocial-technical systems, critical morphological fitness, ecological fitness, ecophysics, ergonomics and human factors (EHF), remote operations, stress, teleoperation
Publisher	VTT Technical Research Centre of Finland Ltd P.O. Box 1000, FI-02044 VTT, Finland, Tel. 020 722 111, https://www.vttresearch.com

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