Sapargaliyev Y. and T. Kalganova (2005) EHW from consumer point of view: Consumer-Triggered Evolution.
Proc. of the International Enformatika Conference, IEC'05, Enformatika pp. 225-230

EHW from consumer point of view: Consumer-Triggered Evolution

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Abstract— Evolvable Hardware (EHW) has been regarded as adaptive system acquired by wide application market. Consumer market of any good requires diversity to satisfy consumers' preferences. Adaptation of EHW is a key technology that could provide individual approach to every particular user. This situation raises a question: how to set target for evolutionary algorithm? The existing techniques do not allow consumer to influence evolutionary process. Only designer at the moment is capable to influence the evolution. The proposed consumer-triggered evolution overcomes this problem by introducing new features to EHW that help adaptive system to obtain targets during consumer stage. Classification of EHW is given according to responsiveness, imitation of human behavior and target circuit response. Home intelligent water heating system is considered as an example.

***Keywords*—**Actuators, consumer-triggered evolution, evolvable hardware, sensors.

I. Introduction

EVOLVABLE Hardware (EHW) is one of the most promising electronic technologies for the wide market applications. Its idea lies in application of *evolutionary algorithm* (EA) [1] towards reconfigurable hardware (HW), or circuit. The main idea of how EHW works is shown on Fig.1. *EA*, navigated by *fitness value*, provides chromosomes. Each chromosome encodes the structure for circuit. Each next hardware structure has to be checked by: putting *circuit stimuli (CS)* through circuit, getting *circuit response (CR)* and comparison last one with *target circuit response (TCR)*. The *fitness value* shows *EA* how close the current hardware structure to required one.

The conventionally designed circuits on consumer market have the limited prescribed list of CS and CR. EHW could process any given CS into any desirable outgoing CR. It could deal with unlimited amount of incoming and outgoing signals due to EA, which changes internal structure of reconfigurable HW continuously, until desired outgoing signals are achieved. This property of EHW could be highly appreciated by millions of potential consumers, whose diverse preferences in form of *CS* could come into EHW, and to whom EHW could outcome the diverse services in form of *CR*.

Manuscript received July 14, 2005.
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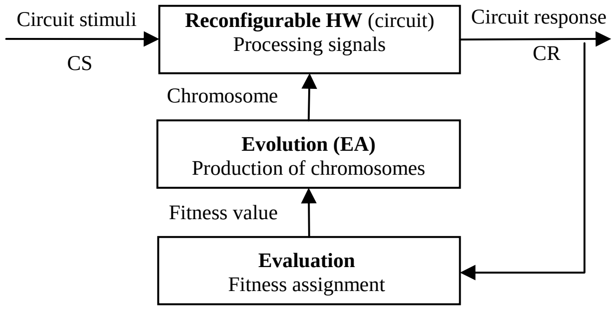


Fig.1. The conceptual scheme of EHW

Beside the range of problems that brake EHW towards the consumer market, the chromosome *evaluation* process is one of most crucial. This is due to the following reasons. 1) Large time-consumption of *evaluation* significantly reduces the *responsiveness* [3] of EHW and thus the potential application market. 2) Another problem of "causing severe damages to EHW or the physical environment" [3] limits the EHW applications to ones that should be evaluated in special conditions, like laboratories or simulated environments, before each interface with consumer [13], [16], [19]. Moreover, the current systems are deprived of the main advantage of EHW, the adaptation ability towards consumers. Instead, nowadays they adapt only towards designer's rules and requirements.

In this paper EHW system has been regarded from *consumer* vs. *designer* points of view. The method of *consumer-triggered evolution* has been proposed in unison with classification given by Sekanina in [5]. It has been described with new classification criteria introduced to EHW applications: *responsiveness, direct /indirect imitation of human behavior* and *target circuit reply*. The method tackles in some way the specified above issues and significantly contributes towards real world EHW applications.

Next section will show the main features of EHW evaluation performance. Section 3 classifies EHW applications. Section 4 proposes the *consumer-triggered evolution* with the application example of water heater system. The last section concludes the paper.

II. Evaluation performance

We refer to notion of fitness function (FF) as the math expression embedded in EHW, which calculates and assigns fitness value to chromosome. The circuit is configured according to chromosome and the circuit response (*CR)* is produced in the form of *analogue electrical signal* [9], [17],

[21], *digital electrical signal* [2], [11], [12], [20] or measurable *behavior* towards environment [10], [13], [14], [18], [19].

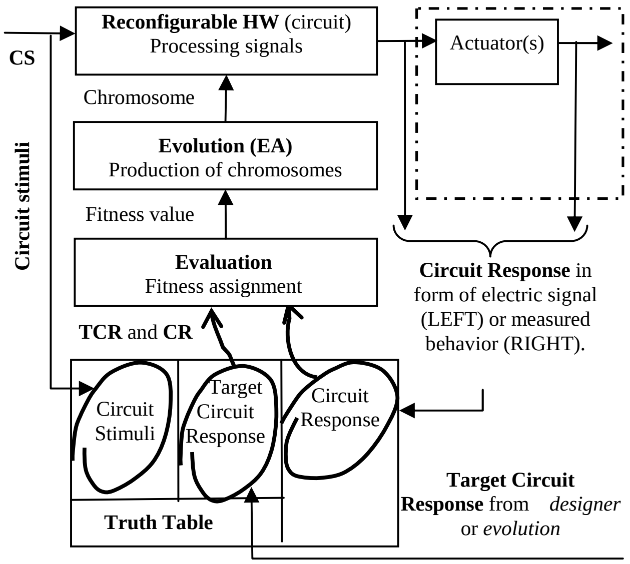


Fig.2. EHW structure performing evaluation. By dashed line on the right upper corner simulation environment is shown.

Let consider FF operation shown in Fig.2. The fitness assignment can be completed based upon multiple *CS-TCR* [11], [21] or only one *CS-TCR* [17]. In first case truth table is usually used. The main task of *Truth Table* is to correspond current *CR* with *TCR and CS,* in order to provide right variables for FF. Then, *Fitness Function (FF)* calculates fitness value and sends it to EA.

The *CR* in form of electrical signal (digital or analogue) is most popular in circuit design. In form of behavior it is often used in evolutionary robotics (ER). Due to difficulty to get precise measure of behavior in a real world, it is most common case to use simulation environment, where the behavior is measured automatically (dashed square, right upper of Fig.2).

According to [6], the FF by its behavior during evolution could be of 4 types: *static*, when none of the values of FF changes [11], [17]; *deterministic dynamic*, if any value of FF is altered by some deterministic rule [19]; *adaptive dynamic*, where some form of feedback from EA is used in some way to influence any of FF value [2], [20]; and *self-adaptive dynamic*, if some FF's parameter(s) directly encoded onto the chromosome [8]. These are supposing only two ways by which variables inside FF can be influenced: *evolution* and *designer*. Designer is one who plans, experiments, composes and improves the EHW before it can be exploited. None of listed FFs by any way concerns with *consumer*. The *consumer-triggered evolution* proposed in this paper take into account consumer point of view.

III. Classification of Appliactions

The first and most general classification of EHW applications is made by Higuchi in [3], where he suggests differing: *circuit design* and *adaptive HW*. The last one, due to its feature adapting itself towards dynamic environment, has potential as a *consumer product*. Up to date there is range of applications that have been implemented as *adaptive HW* [2], [7], [12], [14], [15], [18], [20]. Few of them [2] deal with *consumers*. None of them are able adopting itself towards diverse *consumer* preferences. For the sake of understanding of proposed method, three application classifications are considered: along *responsiveness*, along type of *TCR source*, and Sekanina's classification of evolvable embedded systems [5].

A. Classification along responsiveness

According to [3], *circuit design* and *adaptive HW* differ in when the evolution takes place. If it is "before the online stage", then it is *circuit design.* But if it is "during online interaction between EHW system and environment" [3], then it is *adaptive HW*. In former case the evolution ends when the desired circuit is attained and EHW can be exploited as a *ready-for-use-product* [11], [17], [21]. Fig.3(a) demonstrates that once evolved during *evolution (design) stage* it falls into *consumer stage* at moment T1.

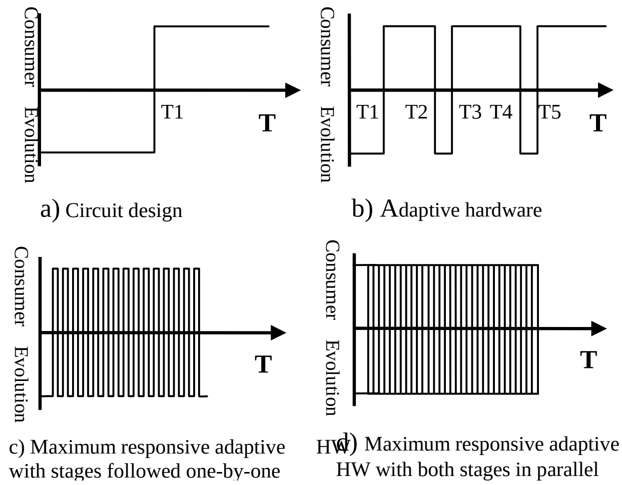


Fig.3. *Behavior* of different types of EHW along time (horizontal) and *consumer* / design stages (vertical) in different types of applications.

In the *adaptive HW* case the evolution is open-ended [2], [12], [14], [15], [18], [20]. Fig.3(b) displays the stages where EHW is being as an *adaptive HW*. As can be seen, at moments T1, T3, T5… the circuit finishes the *design stage* and starts being used as a *product*. At the moments T2, T4… the product does not satisfy *consumer* and falls into *design stage*. Fig.3(c) and Fig.3(d) show the case when *adaptive HW* has maximum *responsiveness* [3]. In this case *evolution* and *consumer stages* are followed one by one Fig.3(c), and both stages are in parallel with inter-exchanging information flow between them (Fig.3(d)).

The *consumers* are ones who are supposed to benefit from *product stage* of EHW described above, without having any idea what the *product* consist of and what intrinsic processes take place inside of EHW.

Let's define: responsiveness of online adaptive system as ability to informationally interact with environment on inherent level of intelligence and which is measured by level of intelligence per time.

Much research in the area of adaptive HW is focused on evolutionary robotics (ER) - systems that try to imitate some aspects of natural system's behavior, characterized by high level *responsiveness*. If we take human behavior, even any small piece of it in real world is characterized by highest *responsiveness*. For example, simple bi-pedal walking is only inherent ability of human; thus, imitating this ability in real world is difficult task. Instead of imitating high responsive behavior of natural systems, it is reasonable to start with lower responsive systems.

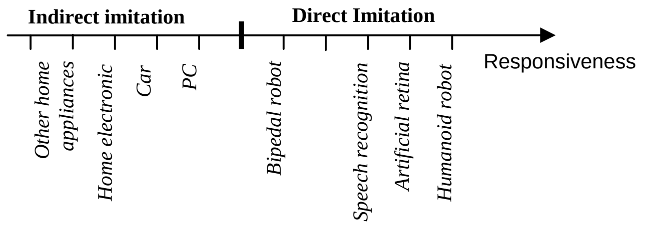


Fig.4. Potential subjects for application of EHW, which are directly and indirectly imitating human behavior along the responsiveness axis.

Let's define: *direct imitation of human behavior* as imitation of time-continuous fragment of human body's act; *indirect imitation of human behavior* as imitation of time-discrete human interaction towards particular subject in the environment. For example, bipedal robot, artificial retina, voice recognition systems are direct imitation of human behavior, because they directly try to imitate behavior that inherent only to human's body. But airplane/car driving auto-pilot system, intelligent home system, intelligent water heater system are indirect imitation of human behavior, because they are trying imitate human's behavior towards the car, home and water heater. For example, human interact with a water heater several times a day, inputting only two kinds of information: "switch on/off" and "starting date-time". Short time and simplicity of this interaction allows easily imitate the human behavior towards water heater. There are a lot of subjects in a human life that are being used by human in a simple periodical time-discrete manner. Some of them are put along *responsiveness* axis on Fig.4: household goods and several artificial intelligence projects. *Time* during which the subject has been in interaction with human can play as gradation criteria of axis.

B. Classification according to Target Circuit Response

TCR is one of variable of FF and can be: a) *pre-set by designer* or b) *obtained from evolution*. The *pre-set by designer TCR* is most common case in circuit design task. For example, in [17] the steady 5 V and a steady 0 V are the *pre-set by designer TCR* against 10 KHz and 1 KHz *CS*. This kind of targets could be called as *ideal targets*, since they do not change during evolution and once the evolution reaches the target the evolution terminates.

The *obtained from evolution TCR* is a case when *designer* has no opportunity to pre-set *ideal target.* Usually such kind of cases appears when one deals with *CR* in the *form of behavior* [10], [13], [14], [18], [19]. The measured behavior (*CR*) of each chromosome is compared with current best one that set as a target (*TCR)* according to comparison rule. Once the current value is better than target, the former replaces the last. The comparison rule can be maximization [14] or minimization [18] of value. The response can be "obtained from the evalution without any transformations (raw fitness value)" [16], or it can be rescaled [18]. Fig.5 shows the difference between two kinds of *TCR*.

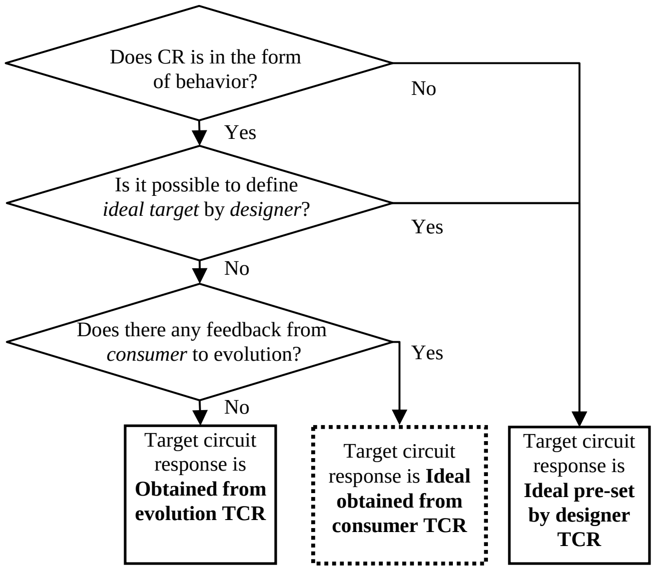


Fig.5. Two kinds of TCR: *obtained from evolution* and *ideal pre-set by designer*. By dashed line is shown *ideal TCR obtained from consumer*.

As it can be seen from Fig.5, the existing types of TCR do not take into account the consumer point of view. The purposed *TCR obtained from consumer* allows eliminating this problem. Whenever consumer changes his habit, the adaptive HW starts *consumer-triggered evolution* and upgrades the current state of a circuit.

C. Sekanina's classification of EHW systems from designer vs. consumer point of view

In [5] Sekanina proposes five different types of EHW applications: *circuit design, self-adaptive systems, self-triggered evolution*. Let analyze types from *consumer vs. designer* points of view.

Circuit design application. In this case the *consumer stage* is assumed to be happened only once in all EHW's life. That is circuit design represents application with minimum *responsiveness* (Fig.3(a)). To start the *design stage* target (*TCR*) must be *pre-set* by *designer*. For example, in [11] the digital form of *CR* is evaluated and fitness value is proportional to the percentage of correct output bits.

Embedded evolutionary design application differs from *circuit design* by its ability anytime to upgrade the current state of a circuit again and again. In other words, it has higher *responsiveness* (Fig.3(b)). The drawback of this type is that in order to fall into next *consumer stage*, the evolution must be tuned and triggered by a *designer*. For example, the prosthetic hand discussed in [2], once evolved for particular patient, can be re-evolved for another patient, or can be evolved periodically for the same patient if his/her electromyography signals have changed. Electromyography signals here play the role of stimuli for circuit, and 6 different digital signals actuating 6 different motions are *pre-set TCR*.

Self-adaptive system has different application destiny due to its feature of updating *TCR* during evolution. This feature enables the system to be responsive to environment. For example, in [18] the task of evolving a digital circuit, which computes a simple hash function mapping a 16-bit address space into an 8-bit one, has been considered. Here two reconfigurable circuits are working in parallel: fist one is in couple with EA in *design stage*; the second circuit is working with environment in *consumer stage*. Each circuit's *CR* is regularly compared with *TCR obtained from evolution*. Every time the *CR* overtakes *TCR*, former one replaces the last; and the correspondent chromosome is downloaded to the second reconfigurable circuit.

Self-triggered evolution is a kind of self-adaptive system where in both cases FF is usually compares the *CR* in the form of measured behavior. *Self-triggered evolution* has to perform the number of one-by-one evolutions, where the finish of previous one is a trigger for starting another one. Usually, each evolution terminates when the pre-set number of generations is completed or evolution time limit is exceeded. In [14] there is evolution in hardware chip for high precision printer image compression. Each time evolution runs the pre-defined number of generations and the best template generated for each stripe is stored in the memory. As soon as the last template for last stripe is stored (designer stage), the compression of whole picture, with the use of all templates, is started (*consumer stage*). The size of compressed stripe is *measured behavior*. The responses are compared to each other. The best one that suits the requirement (minimization task in this case) is evaluated as highest and is set as *obtained from evolution TCR*.

Online evolution according to [5] differs from others by interaction with "real environment during the fitness calculation" and by "applications in ER area" [19]. That is *online evolution* has highest *responsiveness* (Fig 3(c), (d)), i.e. consumer and designer stages are followed each other highly extensively. For example, *responsiveness* of a robot, in comparison with previous examples, is expressed by highly creative and complicated behavior in response to sensory flow from environment. ER never deals with *ideal targets* (robot's behavior), and in this case *TCR* is *obtained from evolution*. So far, there is no real world application of *online evolution* [3].

IV. CONSUMER-TRIGGERED EVOLUTION

Among deep research activity inside EHW area it is easy to loose an idea that consumer market has its own demands to future EHW systems. Despite the considerable research being performed on a subject, all of it made from the point of *designer's* view. *Consumer* has no any influence on *target of evolution*. But it is conventionally known that the "spice" of EHW technique is its capability to adopt itself to widely changeable environment. If we look at the problem from the *consumer's* point of view, we can find that adaptive HW, once it acquired, has to learn *consumer's* preferences and evolve towards it. But how to design EHW system, if in every consumer's case the truth table is going to be different, and it is unreal to evolve every product to every consumer?

Let's imagine EHW system as a product that could be used in every elder's house. Such example can be the Intelligent Water Heating System, which duties are with the help of actuator to turn on the water heating at time when *consumer* is intending to do so. Actuator is accessible by both parties: by person manually and by EHW electrically. For simplicity, let us consider the case when person lives alone in home and he/she has weekly period schedule of water heating. He/she also heats the water once a day and for fixed period of time, i.e. switching off is performed automatically, when time threshold is exceeded. It is difficult for elderly tenant to manipulate with current heating switching panel, but EHW system can learn the *consumer's* lifestyle and actuate on the heater automatically in advance, based on sensor data.

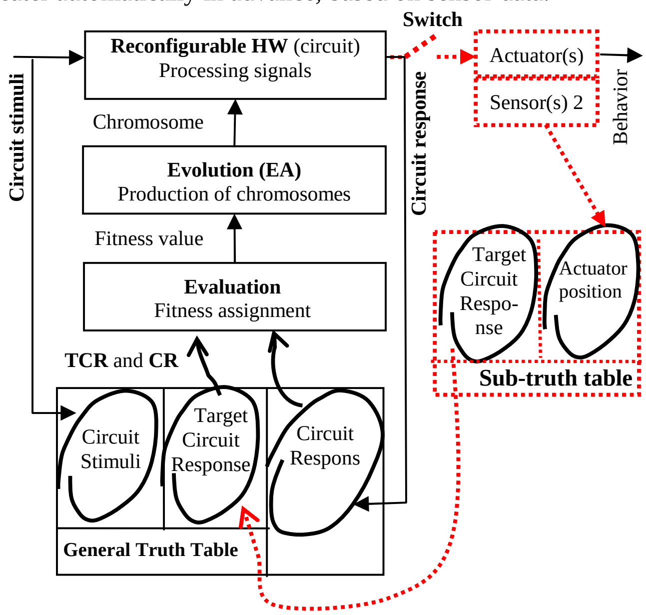


Fig.6. Performance of *consumer-triggered evolution*. By dashed lines are shown the differences from Fig.2.

Let's provide our system, at first, with just only one type of sensory information: time of actuation, i.e. current day of a week, hour and minute values. E.g., consumer's life-style is heating water at 7-00AM in week-days and at 8-00AM in week-ends. This task is similar to one described in [2], where prosthetic hand has to be tuned to particular customer; but the main difference we have that *designer* has no idea of *consumer's* preferences and EHW cannot be evolved in advance.

Thus, the regarded system has to *obtain target* (TCR) from particular *consumer* during *usage stage*. Moreover, the system cannot be exploited at start, i.e. the *circuit response (CR)* cannot be trusted without circuit evolved. Therefore, the EHW system given on Fig.2 can be modified by introducing opened *Switch* between reconfigurable HW and Actuator, as shown on Fig.6. Another important extension is providing EHW with additional sensors at actuators' side. For this reason Sensor2[1] has to be set to get signals about current Actuator's condition.

These two hardware extensions are essence of *consumer-triggered evolution*, which leads to some changes in evaluation performance and at the same time, allows the water heater to perform in common manual regime. In other words, actuator is affected by a consumer manually, while the system could get feedback from Sensor2 on actuator's condition, and thus the system is allowed to *obtain ideal TCR from consumer* during exploitation.

At the first time once EHW system is installed at water heater, there are no any values in truth table. *Switch* is open. The signals from Sensor2 about Actuator's position periodically come to Sub-Truth Table (right of Fig.6). All variables in last one are *pre-set by designer* and located in two columns: "TCR" (ideal in this case) and position of "Actuator" (Fig.7). These values usually are given in actuator's user manual with electro-mechanical description. Based on given Actuator position, Sub-Truth Table finds out correspondent *TCR* and sends last one to General Truth Table. The task of General Truth Table is to set correspondence among all values and send right *CS* and *TCR* to FF. If FF finds the difference between *CR* and *TCR (low fitness value)*, then it orders EA to start *design stage* and sends the order to open *Switch*.

Circuit Stimuli, Time	Target Circuit Response, Actuator on/off
All time	*Off*

a) After installation

Circuit Stimuli, Time	Target Circuit Response, Actuator on/off
Mon,7-00AM	On
All other time	*Off*

b) After first actuation

Circuit Stimuli, Time	Target Circuit Response, Actuator on/off
Mon, 7-00AM	On
Tue, 7-00AM	On
Wed, 7-00AM	On
Thu, 7-00AM	On
Fri, 7-00AM	On
Sat, 7-00AM	On
Sund, 7-00AM	On
All other time	*Off*

c) After first week

Fig.7. Truth tables of Intelligent Water Heater during usage.

Otherwise, if *CR=TCR*, FF orders to close the *Switch* letting *Consumer stag*. At this moment EHW has reached the truth table condition shown on Fig.7(a). *Consumer stage* continues until consumer turns the water heater manually. Immediately after that, *General Truth Table* finds inconsistency between *CR* and *TCR*, opens switch and reports EA to start *design stage*. After first consumer actuation of a *system* on (7-00AM, Monday) evolution has targeted towards truth table condition shown on Fig.7(b).

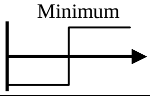
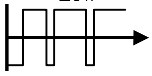
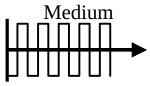
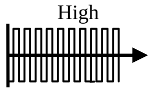
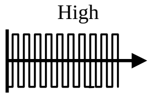
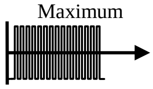
The main target of adaptive HW here is to serve *consumer* and, immediately the system defines the inconsistency between the Actuator's condition and the *circuit response*, it switches itself from *consumer stage* to *design stage*. One EA reaches highest fitness, the *design stage* is closed and *consumer stage* begins. Every day of the first week the truth table is going to be under construction. Since the second week the system is able to serve the customer based on time schedule that has been recorded in General Truth Table (Fig.7(c)). Once evolved, each string of General Truth Table stays unchanged until consumer changes his habit.

[1] The name "Sensor2" comes from supposition that "Sensor1" named after sensor providing *circuit stimuli (CR).*

If a consumer changes his lifestyle waking up later, e.g. from "Monday, 7-00AM" to "Monday, 7-30AM", he will find out the actuator is already turned on. If he will back it in previous position (off) and turn it on at 7-30AM, then the *system* will re-learn towards new preference as it described above, changing time value in General Truth Table. The similar situation happens if a consumer changes rule from "Monday, 7-00AM" to "Monday, 6-30AM" with the difference is just he does not need turn the Actuator back.

The *consumer-triggered evolution* method described above with example of intelligent water heater system could be generalized across all possible potential applications. The amount of "Actuator-Sensor2" couples could be as many as required. It is seeable that main applications which going to benefit from *consumer-triggered evolution* in the first place are *indirect imitations of human behavior*.

TABLE I
APPLICATION CLASSIFICATION SUMMARY OF EHW

System's name	**Responsive-ness**	**TCR type**	**Example, reference**
Circuit design	Minimum 	Pre-set by designer	Logic function [11], signal discrimination [17], digital to analog converter [21]
Embedded evolutionar y design	Low 	Pre-set by designer	Prosthetic hand [2], aircraft recovery [12], recognizing speed limit sign numbers [20]
Self-adaptive systems	Medium 	Obtained from evolution	Image filtration [15], dynamic hashing function [18], adaptive noise filter [4]
Self-triggered evolution	High 	Obtained from evolution	Image compression[14]
Consumer-triggered evolution	High 	Obtained from consumer	Not available
Online evolution	Maximum 	Obtained from evolution	Evolutionary robotics: [13], [19]

Consumer-triggered evolution can be incorporated into Sekanina's classification, as shown in Table 1. This table summarizes the overview made for application classes. *Consumer-triggered evolution* is placed between *self-adaptive* and *online evolution* according to its responsiveness within real world.

V. CONCLUSION

In this paper EHW has been regarded from *designer* vs. *consumer* point of view. Three classification criteria have been introduced for EHW applications: *responsiveness*, *target circuit response* and *direct /indirect imitation of human* *behavior*. Existing EHW applications have been classified according to these criteria. Architecture of *consumer-triggered evolution* has been suggested and described with the example of intelligent water heater system.

Consumer-triggered evolution allows generating the circuits based on consumer requirements. The introduction of coupled "actuator /sensor" allows obtaining *ideal target circuit response* from consumer. The introduction of *switch* prevents undesirable influence from trial-and-error nature of EA toward real world. For ER systems this method can help get ideal chromosome material reducing the evolution time.

REFERENCES

[1] T. Back, D. B. Fogel. Z. Michalewicz, "Handbook of evolutionary computation", Institute of Physics, Publishing, Bristol UK and Oxford University Press, Philadelphia PA, 1997. (New edition: Vol. 1 and 2, Institute of Physics Publishing, Bristol UK, 2000).

[2] J. Torresen, "A dynamic fitness function applied to improve the generalisation when evolving a signal processing hardware architecture", in Proc. of Fourth European Workshop on Evolutionary Computation in Image Analysis and Signal Processing (EvoIASP2002), Springer LNCS 2279, pp. 267-279, April 2002, Kinsale, Ireland.

[3] X. Yao, Tetsuya Higuchi, "Promises and challenges of evolvable hardware", IEEE Transactions on systems, man, and cybernetics—part C: application and reviews, vol. 29, No 1, February 1999.

[4] A. Stoica, "Evolvable hardware for autonomous systems", in tutorials given at the Congress on Evolutionary Computation CEC'03, p. 132, 2003.

[5] L. Sekanina, V. Drabek, "Theory and applications of evolvable embedded systems", in Proc. of the 11th IEEE Int. Conference and Workshop on the Engineering of Computer-Based Systems, Los Alamitos, CA, US, ICSP, 2004, pp. 186-193.

[6] Z. Michalewicz, R. Hinterding, and M. Michalewicz, "Evolutionary algorithms", Chapter 2 in Fuzzy Evolutionary Computation, W. Pedrycz (editor), Kluwer Academic, 1997.

[7] M. Towsey, A. Brown, S. Wright, J. Diederich. Towards Melodic Extension Using Genetic Algorithms, Educational Technology & Society 4(2) 2001.

[8] E. Uchibe, M. Yanase, M. Asada, "Behavior generation for a mobile robot based on the adaptive fitness function", Robotics and Autonomous Systems 40, 2002, pp.69–77.

[9] A. Stoica, R. Zebulum, D. Keymeulen, M. Ferguson, X. Guo, "On two new trends in evolvable hardware: employment of HDL-based structuring, and design of multi-fuctional circuits", page 56-59. 2002 NASA/DoD Conference on Evolvable Hardware, Alexandria, Virginia, USA, July 15-18, 2002, IEEE Computer Society.

[10] G. Buason, N. Bergfeldt, & T. Ziemke, (in press), "Brains, Bodies and Beyond: Competitive Co-Evolution of Robot Controllers, Morphologies and Environments", Genetic Programming and Evolvable Machines, to appear.

[11] T. Kalganova, "Bidirectional incremental evolution in extrinsic evolvable hardware", Proceedings of the 2nd NASA/DoD workshop on Evolvable Hardware, p.65, July 13-15, 2000.

[12] M. Love, K. R. Sorensen, J. Larsen, J. Clausen, "Disruption management for an airline – rescheduling of aircraft". In Applications of Evolutionary Computing, EvoWorkshops 2002, Vol. 2279 of LNCS, pp. 315–324. Springer-Verlag, 2002.

[13] S. Nolfi & D. Floreano (1998 copyright 1999), "Co-evolving predator and prey robots: Do 'arm races' arise in artificial evolution?", Artificial Life, 4 (4), 311-335.

[14] M. Tanaka, H. Sakanashi, M. Salami, M. Iwata, T. Kurita, T. Higuchi, "Data compression for digital color electrophotographic printer with evolvable hardware", in Proc. of the 2nd Int. Conf. on Evolvable Systems: From Biology to Hardware ICES'98, Vol. 1478 of LNCS, pp. 106–114, Lausanne, Switzerland, 1998. Springer-Verlag.

[15] L. Sekanina, "Evolvable components: from theory to hardware implementations", Natural Computing Series, Springer Verlag, 2004.

[16] M. Wahde, "Evolutionary robotics: the use of artificial evolution in robotics", tutorial presented at IROS 2004, Sendai, Japan.

[17] A. Thompson, P. Layzell, R. S. Zebulum, "Explorations in design space: unconventional electronics design through artificial evolution", IEEE Transactions on Evolutionary Computation, Special Issue in "Evolvable Hardware", Moshe Sipper (Ed), pp.167-196, Vol.3, N.3, September, 1999.

[18] E. Damiani, V. Liberali, and A. Tettamanzi, "Dynamic optimisation of non-linear feed-forward circuits", in Proc. of the 3rd Int. Conf. on Evolvable Systems: From Biology to Hardware ICES'00, Vol. 1801 of LNCS, pp. 41–50, Edinburgh, Scotland, UK, 2000. Springer-Verlag.

[19] D. Keymeulen, M. Iwata, Y. Kuniyoshi, T. Higuchi, "Comparison between an off-line model-free and an on-line model-based evolution applied to a robotics navigation system using evolvable hardware", in Proc. of the 6th Int. Conf. on Artificial Life, pp. 199-208, 1998.

[20] J. Torresen, J. Bakke, L. Sekanina, "Recognizing speed limit sign numbers by evolvable hardware", in Proc. of the 8th Int. Conf. on Parallel Problem Solving from Nature (PPSN VIII), Berlin, DE, Springer, 2004, pp. 682-691.

[21] R. S. Zebulum, A. Stoica, D. Keymeulen, "Experiments on the evolution of digital to analog converters", published in the Proceedings of the 2001 IEEE Aerospace Conference, March 10-17 2001, Big Sky, Montana , USA . Manhattan Beach.

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