A Method for Evolutionary Decision Reconciliation, and Expert Theorems

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Abstract—**The author believes that the lack of a theory behind collective intelligence systems and efficient information technologies is one of the reasons for slowing down the development of e-democracy processes. Existing government system, the democracy of the voting majority, is based on ideas that are more than 200 years old and on the well-known Condorcet's jury theorem. One of this theorem's corollaries is that a decision made by the majority vote of a group is worse than a decision made by a single member of the same group if the members of this group make incorrect decisions more often than they make correct decisions. This paper provides proof of two expert theorems proposed by the author. These theorems apply to groups of experts making joint decisions, and they propose that a group of experts involved in reconciliation increase the probability of correct decision if the experts have an opportunity to select and vote on the best third-party decisions. Conditions are provided under which the probability of correct decision by the group of experts approaches 1 as the number of the experts increases. These theorems indicate the direction for development of network programs helping groups of low-competence experts to overcome the Condorcet's border.**

Keywords- collective intelligence systems; Condorcet's jury theorem; e-democracy; crowdsourcing; evolutionary decision reconciliation.

I. INTRODUCTION

The development and use of collective intelligence systems is a popular trend, with individual intelligence no longer being able to keep the pace with the development of our civilization. More than 700 crowdsourcing platforms have been developed and are in use today [1]. Some of them are used directly in e-democracy initiatives [2]. There is an opinion that development of network information technologies will inevitably lead to the emergence of planetary intelligence and the new type of public government—direct e-democracy [3]. The author believes that the lack of a theory behind collective intelligence systems and efficient information technologies is one of the reasons for slowing down this process. Existing government system—the democracy of the voting majority—is based on more than 200-year-old ideas and works by Marquis de Condorcet [16], and no longer fits the spirit of the times. Modern times require a more progressive democracy system relying on the latest network technologies and, most importantly, the new organizational principles for collective intelligence systems.

Collective intelligence is a term first used in mid-1980s in sociology in research of collective decision-making process. NJIT (New Jersey Institute of Technology) researchers defined collective intelligence as the ability of a group to find solutions to a problem that are more efficient than any of the solutions found by individual members of the same group[4]. This concept is used in sociobiology, political science, group reviewing and crowdsourcing applications[5]. It can also be defined as the product of collaboration between the people and data processing methods. In this definition, collective intelligence is referred to as "symbiotic intelligence" and is described by Norman Lee Johnson[6]. According to Lévy, this phenomenon is related to the ability of network information and communication technologies to expand the common body of social knowledge and the range of possible collaboration among people [7].

As described in [8], certain factors related to challenges in human interactions often make a consolidated group decision unreachable, and these environments require the use of efficient coordination methods for group collaboration and the involvement of facilitators in charge of such coordination.

A method for evolutionary decision reconciliation currently researched in Russia is, to a large degree, free of these limitations [9][10]. Specially designed rules for interactions between group members based on genetic algorithms are used as facilitators.

This method can be briefly described as follows. A group of experts receives a problem with a clear goal and clear requirements for solution, which should be presented in text form. Experts work anonymously and interact by exchanging partial solutions with one another via a computer network.

The first stage is solution generation stage when experts create variants of partial solution to the problem based on the project goal. The second and further stages are iterative reconciliation stages when experts evaluate others' solutions and select what they believe to be the best parts of these solutions. Number of variants to be evaluated depends on the interaction rules. Others' solutions for reconciliation are chosen randomly, just like in genetic algorithms. Iterations continue until the allocated time runs out or more than half

 ISBN: 978-1-61208-352-0

experts end up with identical solutions. In the first case, group solution is created as a combination of parts of individual solutions with the largest number of matches. In the second case, group solution is the solution chosen by the majority of experts.

The paper is structured as follows. The next section after introduction describes the new technology developed by the authors that is based on the Evolutionary Decision Reconcillation method. In the third section the Condorcet's theorem is described with discussing the conditions of obtaining the solution with probability, close to one, for crowdsourcing systems.The fourth section presents and proves basic theorems of the new technology that allows experts to overcome the "Condorcet's border". In the fifth section possible areas of the technology application are given. The sixth section concludes the paper.

II. METHOD FOR EVOLUTIONARY DECISION RECONCILIATION

This paper discusses several recent results that, in the author's opinion, may support the principles of metasystem transitions offered by Turchin [11]. Groups of individuals and basic computers were used as components of a system representing the next-generation intelligence. This system demonstrated considerably higher "intelligence" than the combined intelligence of its isolated constituents.

Proposed approach can prove useful in the development of artificial intelligence. This method could help to design symbiotic architectures from neuronets and neurocomputers, computers and their networks, groups of people and genetic rules working as a single unit. Protasov successfully applied these rules to improve human intelligence [12] and the "group intelligence" of robot groups [13]. A similar approach could perhaps be used to construct hierarchical networks with cascaded "intelligence" gains at each level.

For example, a popular target distribution problem can be formulated as follows: there are m robots with calculators and n targets. Each calculator has coordinates of all robots and all targets. The goal is to split robots and targets in pairs so that if $m < n$ or $m = n$, then there is at least one robot for every target, and if $m > n$, then there is at least one target for every robot, and the sum of distances S between robots and their paired targets is minimal.

Experience shows that the generic method is sufficiently effective in solving this type of problems. The most trivial solution would be as follows: since the every calculator of every robot i has location data for all robots and targets, it can build a set of possible target distributions using standard crossover, mutation, estimation and selection operations, through some iterations will result in less than optimal solutions. Since all calculators use the same algorithm and have identical data sets, they generate identical solutions when they operate independently, and each robot will choose its target. The advantage of the proposed method is that it can be used to speed up the calculations by a factor of m by making a more efficient use of resources.

In [13], a method for distributed calculations was proposed whereby one super-calculator coordinates the work of other calculators to reduce the overall time required to make a decision.

For the target distribution problem, the following algorithm was proposed: each calculator will use its own random number generator to create one possible solution, which will likely be far from optimal. All proposed solutions will be different. Then the calculators will communicate and exchange proposed solutions. After that, the calculators reject the worst half of the overall number of solutions, certain mutations in proposed solutions, and exchange solutions again. This process will continue until only one solution remains. Then the calculations will stop, and each robot will have the best solution in its possession.

A demo program called COLLINTROB was developed and tested on Delphi platform. It demonstrated that the time to reach a common decision was inversely proportional to the number of calculators in system. Some experiments simulated failures of a certain number of calculators and demonstrated that calculator failures did not degrade the quality of solution (the result was within 5% from the ideal solution), but the time required to reach the decision increased proportionally $M / (m-k)$, where k is the number of failed calculators.

The analysis of these experiments suggests that the "collective intelligence" of calculators incorporated in the super-calculator increases and it becomes greater than the intelligence of individual calculators on a certain class of problems. In other words, in this case we see the metasystem transition resulting in the occurrence of "greater mind" consisting from artificial components with a lower level of "intelligence".

The same rules of interaction between the individual components of such a "collective mind" were used in tests using human subjects and were applied to create the new kind of collective intelligence in the so-called Method for Evolutionary Decision Reconciliation (MER) [9].

The variables, such as the number of participants or the number of proposals discarded at each step, can vary depending on the type of problem and can be selected experimentally.

The Method for Evolutionary Decision Reconciliation was tested in groups of 4 to 20 male students in different areas including collective poetry, music composition, creation of psychological portraits, development of simple computer program, selection of the best move in a chess game, direct sales, portrait painting, and creation of abstract diagrams.

These experiments confirmed that collective intelligence exceeds the combined intelligence of individual contributors and shows the phenomenon of knowledge transition from the strongest contributors to the weakest. This method also allows ranking the contribution of individual participants to the final product. It usually did not take long to solve simple tasks, and as a rule, the duration of experiments did not exceed two hours, with Eysenck tests taking approximately 30 minutes). Students were quite enthusiastic about these experiments, and excited about being a part of collective mind exceeding their individual capabilities.

III. CONDORCET'S JURY THEOREM

Protasov et al. [14] provide the results of computer modeling for a collective decision-making process using the new technology. Certain specific competence levels of experts, who generate ideas and evaluate others' solutions, were shown to amplify the intelligence when the experts were working with the group. This paper contains the proofs of theorems confirming this effect.

Let us start with discussing the limitations of collective intelligence systems following from Condorcet's jury theorem. One of the definitions of Condorcet's jury theorem [15] is as follows:

Let us assume that one of the two decisions proposed to the jury is correct, and each jury member, on average, makes correct decisions more often than not. The theorem claims that as the number of participants increases, the probability that the correct decision is made tends to one.

The probability that the group of *M* experts makes correct decision, assuming that each of these experts makes correct decision with the probability of *G*, can be calculated as follows:

$$K_0 = \sum_{i=0}^{\frac{M-1}{2}} \binom{i}{M} G^{M-i}(1-G)^i \tag{1}$$

With *G>0.5* and $M \to \infty$, we have the Condorcet effect, and the probability of correct decision by the group of experts $K_0 \to 1$, but with *G<0.5*, the probability $K_0 \to 0$. In other words, *G=0.5* is the border value that weak experts are unable to overcome.

The Condorcet's effect is used in modern crowdsourcing systems where tens and hundreds of thousands of users find the best decisions. Unfortunately, G is not guaranteed to be always greater than 0.5. We will show that if we give experts with 0<G<0.5, who did not make their decisions for any reason, an opportunity to view decisions of other people and select the best of them, then under certain conditions the probability that a group of such experts makes a correct decision by majority vote tends to 1 with the increase of the number of experts in the group, or in other words, such a group is able to overcome the Condorcet's border.

The purpose of this research is to evaluate the competence of experts that guarantees that the probability that the group of experts makes the correct decision approaches 1 as the number of experts increases.

Experts are supposed to use evolutionary decision reconciliation in their collective work.

This work presents proofs for two theorems that help to forecast the results of group effort based on expert competence levels, offers several corollaries and discusses benefits and use cases of the new technology.

IV. EXPERT THEOREMS

A. *Theorem 1*

Let us assume that at the individual decisions stage, each expert makes correct decision with the probability $0 < G_P < 0.5$, incorrect decision with the probability $0 < G_N < 0.5$, or no decision with the probability $G_V = 1-(G_P + G_N)$, and at the group decisions stage, an expert that did not make any decision selects correct decision out of several third-party decisions with the probability E_P (assuming it is available), incorrect decision with the probability E_N, or no decision. The theorem proposes that when $G_P + E_P \frac{1-(G_P+G_N)}{E_P+E_N} > 0.5$ condition is met, the probability that correct decision is selected by majority vote at reconciliation stage increases and tends to one as the number of experts increases.

Proof. At the individual decisions stage, the expected value of the number of experts P_0 who make the right decision (subgroup *P*) is $G_P M$ (where M is the total number of experts); the expected value of the number of experts N_0 who make the wrong decision (subgroup *N*) is $G_N M$; and the expected value of the number of experts V_0 that make no decision (subgroup *V*) is $G_V M = (1 - G_P - G_N)M$.

At reconciliation stage, experts from subgroup *V* will join experts in subgroups *P* and *N* in proportion to E_P and E_N, while subgroup V will reduce in proportion to $E_V = 1 - E_P - E_N$. Let us designate P_i, N_i and V_i as the expected values of the number of experts in respective subgroups at the i-th iteration of the reconciliation stage.

Iteration 1: $P_1 = (G_P + E_P G_V)M$, $N_1 = (G_N + E_N G_V)M$, $V_1 = E_V G_V M$.

Iteration 2: $P_2 = (G_P + E_P G_V + E_P E_V G_V)M$, $N_2 = (G_N + E_N G_V + E_N E_V G_V)M$, $V_2 = E_V^2 G_V M$.

…

Iteration i: $P_i = G_P M + E_P G_V M \sum_{k=0}^{i-1} E_V^K$,

$N_i = G_N M + E_N G_V M \sum_{k=0}^{i-1} E_V^K$, $V_i = E_V^i G_V M$.

With $i \to \infty$, if we replace $\sum_{k=0}^{i-1} E_V^K$ with its limiting value $\frac{1}{1-E_V}$ and the last term of geometric progression V_i with zero, we will get the expected values P_B, N_B and V_B for the numbers of experts in groups *P*, *N* and *V*:

$$P_B = (G_P + \frac{E_P G_V}{1-E_V})M, \quad N_B = (G_N + \frac{E_N G_V}{1-E_V})M, \quad V_B = 0. \tag{2}$$

 ISBN: 978-1-61208-352-0

With $G_P + E_P \frac{1-(G_P+G_N)}{E_P+E_N} > 0.5$, the majority of the group will make the right decision. Since with $M \to \infty$, the P_B / M ratio is the probability that the expert makes correct decision at the end of reconciliation stage, the condition of Condorcet's theory is met, and our theorem is therefore proven.

For practical use and theoretical research, the condition of this theorem can be expressed as

$$\frac{E_P}{E_N} > \frac{1-2G_P}{1-2G_N}. \qquad (3)$$

Let us review several corollaries of (3):

If the experts in the group have weak decision-making capability ($G_P < G_N$), then for the probability that they make correct decision to be more than *0.5*, they need strong evaluation capability ($E_P > E_N$).

If the experts in the group have strong decision-making capability ($G_P > G_N$), then for the probability that they make correct decision to be higher than *0.5*, even weak evaluation capability is sufficient ($E_P < E_N$).

If both capabilities are weak in the group, experts will not be able to make correct decision with probability higher than *0.5*. Moreover, the probability that the vote results in correct decision decreases and tends to zero as the number of such experts increases.

B. Theorem 2

Suppose that at the individual decision stage, every expert makes correct decision with the probability of $0 < G_P < 0.5$, incorrect decision with the probability of $0 < G_N < 0.5$, or no decision with the probability of $G_V = 1-(G_P+G_N)$; and at the first iteration of reconciliation stage, each expert who did not make a decision receives a randomly selected third-party decision, and then the expert correctly evaluates the correctness of this decision with the probability of E_R, and as a consequence, either submits or does not submit this decision for a vote.

The theorem proposes that when $E_R \frac{1-(G_P+G_N)}{G_P+G_N} > \frac{1-2G_P}{2G_P}$ condition is met, the probability that correct decision is selected by majority vote at the first iteration of reconciliation stage increases and tends to one as the number of experts increases.

Proof. At the individual decisions stage, the expected value of the number of experts P_0 who make the right decision is $G_P M$; the expected value of the number of experts N_0 who make the wrong decision is $G_N M$; and the expected value of the number of experts that make no decision V_0 is $G_V M = \{1-(G_P+G_N)\}M$. At the first iteration of the reconciliation stage, the number of correct decisions will increase by $\frac{E_R G_P G_V}{G_P+G_N} M$, because the probability that correct decision is selected out of all decisions made is $\frac{G_P}{G_P+G_N}$; the probability that this selection is made by an expert who did not make a decision is G_V; and the probability that this decision is included in the group's decision is E_R. Therefore, the expected value of the number of correct decisions at the first iteration is $P_1 = G_P M + E_R G_P \frac{1-(G_P+G_N)}{G_P+G_N} M$. Let us make the same condition we used in the previous theorem, that $\frac{P_1}{M} > 0.5$ when $M \to \infty$, or after transformations, the condition of the theorem $E_R \frac{1-(G_P+G_N)}{G_P+G_N} > \frac{1-2G_P}{2G_P}$. Since when $M \to \infty$, the P_1 / M ratio is the probability that the expert makes correct decision at the first iteration of reconciliation stage, the condition of Condorcet's theory is met, and our theorem is therefore proven.

V. TECHNOLOGY FOR EVOLUTIONARY DECISION RECONCILIATION

There are many groups of experts that are not capable of making their first opinion correct with probability higher than *0.5*. Theorems proven above give us a hope for development of modern network programs that are able to overcome Condorcet's border and can be used efficiently in e-democracy systems.

The phenomenon when the probability that a group of experts makes correct decision increases due to the use of abilities of experts in selection of best decisions gave an opportunity to develop a new information technology for evolutionary decision reconciliation [9]. Multiple experiments in different creative fields confirmed the efficacy of the new approach. For example, collective intelligence was used to solve complex chess problems beyond the capabilities of individual group members; a group of witnesses effectively built a facial composite; a group of automated translators translated texts with higher quality than that of individual translations. IQ measurements using Eysenck verbal tests demonstrated group intelligence when the group was able to find correct answers to all 50 questions within a limited period of time [16]. One of the benefits of the new technology is that it gives an opportunity for objective measurements of individual expert contributions to the group project—both as idea generators and as evaluators of third-party decisions—and for development of hierarchical collective intelligence systems based on these measurements.

VI. CONCLUSION

The aforementioned results suggest that the evolutionary decision reconciliation technology is advisable for use in project management systems and e-democracy systems. New opportunities offered by this technology can expand the circle of potential contributors to collective solutions. Anonymous group effort, when experts work with ideas in text form without the need for personal contact with individuals with whom such contact is difficult due to psychological reasons, helps to fully unleash the intellectual potential of every expert. Use of genetic algorithms as group facilitators ensures quick convergence of the iterative process used to generate consolidated text. The technology based on evolutionary reconciliation method provides an opportunity to evaluate objectively the contribution of each expert to the consolidated product, and to establish a hierarchically organized self-governing crowdsourcing community[16]. Expert theorems proved in this work allow forecasting the probability that the decision will be correct as long as expert competence levels are known. The author and his colleagues are planning to continue research focused on practical use of this method to solve a variety of creative problems that expert communities are facing, and on the measurement of expert competence levels.

ACKNOWLEDGEMENTS

This work was supported by the Russian Foundation for Basic Research, grant #13-07-00958 “Development of the theory and experimental research of a new information technology of self-managed crowdsourcing”.

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