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DEPTH-WIDTH TYPE CRITERIA APPROBATION FOR TREE SHAPE CONTROL FOR THE MONTE CARLO TREE SEARCH METHOD

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This paper is devoted to the scientific problem of improvements of the Monte Carlo Tree Search (MCTS) method. The object of research is the process of performing a tree search using the MCTS. The subject of research is the MCST improvement technique with control of the search tree shape by usage of the previously proposed be the authors *DWC* (Depth/Width Criterion) and *WDC* (Width/Depth Criterion) criteria. This technique was named Monte Carlo Tree Search with Tree Shape Control (MCTS-TSC). The research methods are based on the theory of data structures and analysis methods.

The aim of the study is to conduct extended study of the previously proposed MCTS-TSC technique for improvement of the MCTS method. In particular, the aim is to approve that the *DWC* and *WDC* tree shape control criteria ensure the better move selection and increasing player strength compared to the standard Monte Carlo Tree Search with Upper Confidence bounds applied to Trees (MCTS-UCT) technique.

To achieve the aim, the following tasks were set: to conduct a set of experiments according to the developed approbation methodology to approve that the *WDC* criterion of the MCTS-TSC technique is able to improve the MCTS method; to conduct a set of experiments according to the developed approbation methodology to approve that the *DWC* criterion of the MCTS-TSC technique is able to improve the MCTS method.

Both *WDC* and *DWC* criteria of the MCTS-TSC technique were tested on a series of games of Connect Four between a player, which used the MCTS-TSC technique, and a player which used the MCTS-UCT technique. Different parameters for tuning the formulas of the *WDC* and *DWC* criteria of the MCTS-TSC technique were used in the experiments.

The paper describes the methodology of the approbation of the MCTS-TSC technique with usage of the *WDC* and *DWC* criteria compared to the MCTS-UCT technique and conducts comparative analysis of the results of the experiments. The MCTS-TSC player won from 30% to 70% more games than the MCTS-UCT player for some search tree shapes, when *WDC* criterion was used, and from 19% to 52% more games, when *DWC* criterion was used. So, ability of the proposed MCTS-TSC technique to improve the MCTS method was approved for both criteria, *WDC* and *DWC*.

Key words: depth-width type criteria, Monte Carlo tree search method, MCTS, MCTS-UCT, MCTS-TSC, search tree shape control.

1. Introduction

This paper is devoted to the scientific problem of improvements of the Monte Carlo Tree Search (MCTS) method [1]. This method, after its appearance, has become one of those methods for the field of artificial intelligence, without which it is difficult to imagine the solution of many problems in this field. The MCTS method is currently one of the most popular search methods due to the massive data volumes and high complexity of solutions in artificial intelligence problems. MCTS relies on the Monte Carlo method, using a stochastic search process instead of exhaustive search which is unsatisfactory for such large datasets due to time constraints. The MCTS method has shown high efficiency in solving many classes of artificial intelligence problems. However, simultaneously with the further development and emergence of new ways to improve this method, the complexity of the tasks and the volume of data for these tasks also increase. That is why research of other new improvement techniques of the MCTS become even more actual, now.

2. Literature review and problem statement

Since the tree search method MCTS has been known for enough long time, research on this method has already been carried out in many works by different researchers. Good reviews of different approaches and ways of further development of MCTS are made in works [1 – 4]. It should be noted that MCTS researchers, as a rule, try to improve the basic *UCB1* (Upper Confidence Bound) formula of the MCTS method using, figuratively speaking, “internal” criteria. These approaches take into account different cases of the win/loss ratio, heuristics based on knowledge of the features of the application domain (game), specific cases of positions that may arise during the game, etc. But the criteria that reflect, figuratively speaking, “external” abstract and identical for all games data structures such as the search tree and its shape, were used infrequently, although such publications also exist [5 – 7]. But even in these cases, authors propose mainly only such a criterion as the branching degree of the tree vertices. This criterion well reflects the potential width of the already constructed subtree that is directly under this vertex. However, it is insufficient to estimate both the actual width and the actual depth of the entire subtree of this vertex. Insufficiency follows from that the criterion "branching degree of a vertex" shows only the local width at this particular vertex. This criterion says nothing about either the total width of the entire subtree that is under this vertex, or the shape (narrow, wide, etc.) of this subtree. Though, this criterion effectively reflects the potential width of the constructed subtree directly under a vertex, however, it is insufficient for estimating the actual width and depth of the entire subtree.

The "branching degree of a vertex" only indicates the local width at that vertex. But it provides no information about the total width of the entire subtree or its overall shape, such as whether it is narrow or wide.

In some papers from the list of references of the paper and in the content of this paper the “strength of a player” term is used for explanations of researches. Let us give the definition how this term is treated in the context of the MCTS method in this paper.

Strength of a player is a relative entity which is measured in numbers of wins of this player. Who of two players have more wins in a series of games, this player has greater strength.

An interesting result was obtained in [8], in which the authors studied the MCTS method on the Mancala game. They were able to obtain a search tree that was more complete (and therefore wider) at the initial levels of the tree and more scattered (and therefore with narrower branches) at deeper levels. At the initial stage of the search, the emphasis shifts toward exploration when choosing between little-explored moves and moves which were already assessed as good. This leads to constructing a wider tree initially. After some search time, the emphasis shifts toward using the explored good moves and, as a result, the tree begins to grow deeper rather than wider. And as the authors of the [8] work note, constructing a tree of such a balanced shape had a positive effect in increasing the player's strength. This conclusion emphasizes the existence of a relationship between the shape of the MCTS search tree and the player's strength, that is, the efficiency of this search.

Previously, the authors of this paper in [9] proposed some general depth-width (*DW*) type criteria for the tree shape control. These criteria are based on calculating the ratio of the depth of subtrees to their width for each vertex of the tree or vice versa and were taken in some way in the UCB1 formula. Besides, a method for further development of the MCTS method, which is based on these criteria and which was called Monte Carlo Tree Search with Tree Shape Control (MCTS-TSC) was proposed in [9], too. After approbation the first variants of the *DW* type criteria, two new criteria of this type were proposed lately at the next stage of the research in [10]. But these the last criteria were not tested deeply yet. So, extended study of the new *DWC* and *WDC* criteria is the actual problem for the further research.

Let us briefly consider two new *DW* type criteria, which were proposed firstly in [10]. The criteria are *DWC* (Depth/Width Criterion) and *WDC* (Width/Depth Criterion). *DWC* and *WDC* criteria are defined as follows:

$$DWC = C_R \times \left(\frac{ND}{NW} - C_{DW}\right), \tag{1}$$

$$WDC = -C_R \times \left(\frac{NW}{ND} - C_{WD}\right) = C_R \times \left(C_{WD} - \frac{NW}{ND}\right), \tag{2}$$

where,

DWC – Depth/Width Criterion;

C_{DW} – depth-width parameter (coefficient), which determines the desired (reference) shape of the tree for the *DWC* criterion;

WDC – Width/Depth Criterion;

C_{WD} – width-depth parameter (coefficient), which determines the desired (reference) shape of the tree for the *WDC* criterion;

C_R – regulation parameter (coefficient) for decrease/increase of the influence of the *DW* type criteria;

ND – Node Depth, i.e. depth of a subtree of a certain vertex;

NW – Node Width, i.e. width of a subtree of a certain vertex.

The new *DW* type criteria (their place is marked in red in the formula (3)), are used to fine-tune the main *UCB1* formula [1] of the MCTS method by adding their values to the C_{UCB1} parameter. Because *UCB1* formula now depends on the *DW* criteria for tree shape control (*TSC*), it is now named $UCB1_{TSC}$:

$$USB1_{TSC} = \frac{NodeWins}{NodePlayouts} + 2 \times (C_{USB1} + DW) \times \sqrt{\frac{2 \times \ln(ParentPlayouts)}{NodePlayouts}}, \tag{3}$$

where,

NodeWins – the number of gained game wins when a given vertex was selected;

NodePlayouts – the number of times the game passed through a given vertex;

ParentPlayouts – the number of times the game passes through the parent vertex of a given vertex;

C_{UCB1} – a parameter for configuring the search process;

DW – one of the *DW* type criteria.

These formulas (1), (2) and (3) are described in detail in [10]. Formula (3) will now take into account not only the current probabilities of the next moves (which may not be accurate enough) in a certain vertex, but also the current shape of the subtree of this vertex. The result is as follows. If the shape of a certain subtree began to move away from the typical shape for a given problem in a certain direction (for example, towards expansion), adjustments are made. The modified parameter C_{UCB1} will give preference to such a vertex among the next vertices with the same probability which will direct the further construction of the tree in the opposite direction (towards deepening). In result, the tree shape will become closer to a more typical shape for this problem (game).

The first approbation of the MSTC-TSC technique with usage of the new *DWC* and *WDC* criteria [10] showed their good results in certain cases. But then only some simple experiments of the criteria evaluation were conducted and additional experiments were needed. So, the paper is devoted to more strong approbation of these criteria usage under more systematic methodology of conducting experiments.

3. The aim and objective of the study

The aim of the study is to conduct extended study of the previously proposed MCTS-TSC technique for improvement of the MCTS method. In particular, the aim is to approve that the *DWC* and *WDC* tree shape control criteria ensure the better move selection and increasing player strength compared to the standard MCTS-UCT technique.

To achieve the aim, the following tasks were set:

– to conduct a set of experiments according to the developed approbation methodology to approve that the *WDC* criterion of the MCTS-TSC technique is able to improve the MCTS method;

– to conduct a set of experiments according to the developed approbation methodology to approve that the *DWC* criterion of the MCTS-TSC technique is able to improve the MCTS method.

4. Methodology of the *DWC* and *WDC* criteria study

4.1. Important notes from previous investigations

Let us consider an experimental approbation of the MCTS-TSC technique which uses the proposed *DWC* and *WDC* criteria. The approbation was conducted for the MCTS-TSC search tree shape control method compared to the standard MCTS-UCT (Monte-Carlo Tree Search with Upper Confidence bounds applied to Trees) technique of implementing MCTS search method. The experimental verification was performed on the Connect Four game, the branching degree of which is B = 7.

Let us note a few important points for this study and analysis.

In early studies of the MCTS method [1], it was found that the ability of the MCTS search in finding the best subsequent solutions (moves) depends on the value of the C_{UCB1} parameter. Besides, these studies also found that although for many application tasks (games) one of the best values of this parameter is $C_{UCB1} = 1/\sqrt[2]{2} = 0.707$, this is not the case for all tasks. In general, for different problems the best value of C_{UCB1} may be different and is determined experimentally.

During the first series of MCTS research experiments an important fact which had to be taken into account for the next experiments was established by the authors of this paper. The fact concerns implementation of the Connect Four game players which use MCTS search. If both players have the same value of the C_{UCB1} parameter, the 2nd player (i.e. the one who starts the game second) in the vast majority of cases wins over the 1st player. I.e. in the Connect Four game between two players playing by the using the MCTS search, the second player has a certain advantage and turns out to be stronger.

4.2. Methodology of the preliminary stage of the study

Taking into account the above, the preliminary stage of testing was first performed. At this stage, the following was done:

– for the Connect Four game the best value of the C_{UCB1} parameter was determined for implementing the strongest player of this game; the above-mentioned fact of a certain advantage of the second player was taken into account;

– typical shapes of the search trees (*NW*/*ND* and *ND*/*NW* ratios) for the Connect Four game were determined; these tree shapes were obtained at different set computational budgets using the standard MCTS-UCT technique of the MCTS search method;

– for each set computational budget, intermediate shapes (*NW*/*ND* and *ND*/*NW* ratios) were determined; these shapes were fixed for the search trees built after performing each 10% of the budget iterations.

To determine the best value of the C_{UCB1} parameter, both players played according to the standard MCTS-UCT technique with different values of the C_{UCB1} parameter from 0.3 to 1.4 with the step of 0.05. The games were played alternately as the 1st player and as the 2nd player. The general scheme of conducting the games of the preliminary stage of the study was as follows:

– the 1st player played with some parameter value, for example $C_{UCB1} = 0.7$, and the 2nd player played with another value, for example $C_{UCB1} = 0.5$;

– then, on the contrary, the 1st player played with the parameter value of $C_{UCB1} = 0.5$, and the 2nd player played with the value of $C_{UCB1} = 0.7$;

– for each value of the C_{UCB1} parameter, the sum of winnings was calculated when both the 1st and 2nd players played with such a C_{UCB1} value; the same sums were calculated for losses and draws.

As a result of this preliminary stage of the research, it was found that the best value of the C_{UCB1} parameter for the Connect Four game is $C_{UCB1} = 0.55$.

Therefore, the main stage of the approbation on the Connect Four game was performed precisely at the set value of the main parameter $C_{UCB1} = 0.55$ for both of these players in all cases. This value was used by each player when it played the game as the 1st player and when as the 2nd player. This allowed to achieve equivalent comparing the strength of the MCTS-TSC player with control of the search tree shape, and the standard MCTS-UCT player.

To determine the typical shape of the search tree for the Connect Four game, it was necessary to take into account the fact that trees built for different numbers of search iterations (different computational search budgets) will have different numbers of tree vertices. Usually, number of tree vertices equals to the number of search iterations, if one vertex is added at each iteration. Besides, when different computational budgets are set, different tree shapes, i.e. the width-to-depth ratio *NW*/*ND* and the depth-to-width ratio *ND*/*NW*, will be obtained as a rule, too. Therefore, in order to obtain more reliable statistics for the comparison of the MCTS search by the MCTS-TSC and MCTS-UCT techniques, a set of games between them was conducted with different computational budgets. The typical shape of the search tree was determined separately for each of these budgets.

Further, using the standard MCTS-UCT technique, the tree shapes (*NW*/*ND* and *ND*/*NW* ratios) were also determined after performing each 10% of iterations of a set budget. These intermediate shapes were fixed during construction search trees for each of the computational budget values used in the experiments.

All the tree shapes determined at this preliminary stage were taken to conduct a set of games in the main stage of the experiments.

4.3. Methodology of the main stage of the study

At the main stage of experimental verification of the proposed theoretical developments, the following cases were considered:

– testing the efficiency of a player which used MCTS-TSC technique with control of the search tree shape by the *WDC* criterion, compared to a player which used the standard MCTS-UCT search technique;

– testing the efficiency of a player which used MCTS-TSC technique with control of the search tree shape by the *DWC* criterion, compared to a player which used the standard MCTS-UCT search technique.

The games between the MCTS-TSC and MCTS-UCT players for each of these cases were performed according to the following general scheme:

1. First, the best value of the C_R parameter was determined for a given value of the desired tree shape parameter C_{DW} or C_{WD} for the MCTS-TSC player, i.e. the value at which the MCTS-TSC player played the strongest in this case. This value was determined separately for each of the *WDC* and *DWC* criteria. Since the C_R parameter has a similar regulatory nature as the C_{UCB1} parameter, the determination of the best value of the C_R parameter for the MCTS-TSC player was performed experimentally in a similar way to the determination of the C_{UCB1} parameter value.

2. For each partial case of the study, 20 games of the Connect Four game were conducted: 10 games were conducted when the MCTS-TSC player played first and 10 games were conducted when the MCTS-UCT player played first. After that, the number of wins of each player when he started the game first and when he started the game second was summed up. The number of draws were also summed up.

3. A set of experimental games of the Connect Four game was conducted for the following research parameters, combining these parameters according to the principle of "each with each" (each such combination of parameters gave a partial case of the study):

– the 1st parameter which set the shape control criterion, *WDC* or *DWC*;

– the 2nd parameter *Iter* which set the computational budget in the form of the number of iterations of the search execution;

– the 3rd parameter which set the desired (typical) shape of the search tree: C_{WD} or C_{DW};

– the 4th parameter *PB* (Part of Budget) which set percentage (in fractions of a unit) of the number of iterations of the set budget, after execution of which the desired tree shape parameter (C_{WD} or C_{DW}) for this budget was determined.

Let us consider these parameters in more detail.

The 1st shape control criterion parameter, *WDC* or *DWC*, set the formula, (1) or (2), by which the shape of the tree will be controlled.

The 2nd *Iter* parameter set the computational budget (number of search iterations) that was allocated to making a decision about each player's next move. Our study was carried out for the following computational budget cases:

– 50000 iterations;
– 100000 iterations;
– 150000 iterations;
– 200000 iterations;
– 250000 iterations;
– 300000 iterations.

The 3rd parameter of the desired shape of the search tree C_{WD} (for the *WDC* criterion) or C_{DW} (for the *DWC* criterion) set the ratio of the desired width of the search tree to the desired depth of the search tree, or vice versa:

$C_{WD} = DSW/DSD$,

$C_{DW} = DSD/DSW$,

where,

DSW – desired (reference) shape width of the search tree,

DSD – desired (reference) shape depth of the search tree.

The 4th parameter *PB* set the percentage (in fractions of a unit) of the number of iterations of the computational budget (*Iter* parameter) for each partial case of the approbation. The shape of the search tree that the tree obtained after executing this percentage of the budget was set as the desired tree shape ($C_{WD} = DSW/DSD$ or $C_{DW} = DSD/DSW$) for this partial case study.

Let us consider the meaning of the *PB* parameter from the point of view of the process of constructing an MCTS search tree with tree shape control using the MCTS-TSC technique. Recall that at the beginning of tree construction, the shape of this tree is relatively narrow. Then during the construction, it is quickly stretched in width, since the branching degree of the Connect Four game is 7. The *PB* parameter value, for example *PB* = 0.3, means that the reference desired shape of the search tree is set to the shape that the tree has after executing 30% of the specified iteration budget. This is just the shape, which MCTS-TSC will try to direct the tree construction process to. As a result, the effect of controlling and correcting the shape of the search tree will be as follows. During the first 30% of tree construction iterations (i.e., when the current tree shape is narrower than desired), the use of the *WDC* and *DWC* criteria will direct the tree construction towards its additional expansion compared to how the standard MCTS-UCT technique does it. And during all subsequent iterations of tree construction from 30% onwards (i.e. when the current shape of the tree becomes wider than desired), the use of the *WDC* and *DWC* criteria will, on the contrary, direct the tree construction towards its additional deepening compared to MCTS-UCT.

5. Results of the experiments of the *DWC* and *WDC* criteria study

5.1. Results of the experiments of the *WDC* criterion

A sets of Connect Four games was played to test the MCTS-TSC technique compared to the standard MCTS-UCT technique when the *WDC* tree shape control criteria was used.

Each partial set of games was played both when the MCTS-TSC player made the first move (10 games) and when the MCTS-UCT player made the first move (10 games) for each of the computational budget cases (6 cases). Thus, for each partial study, when changing the parameter *PB* from 0.1 to 1 with a step of 0.1, (10 + 10) * 6 = 120 games were played.

After that, for each value of the parameter *PB*, the total number of wins of each player, as well as the number of draws, was summed up. The obtained values were used to construct a summary comparative diagram of the results shown in the Figure № 1.

The symbols and colors in the Figure№ 1 have the following meaning:

– the abscissa axis shows the values of the parameter *PB*;

– the ordinate axis shows number of wins of each player, MCTS-TSC (blue color) and MCTS-UCT (orange color) as well as number of draws (gray color).

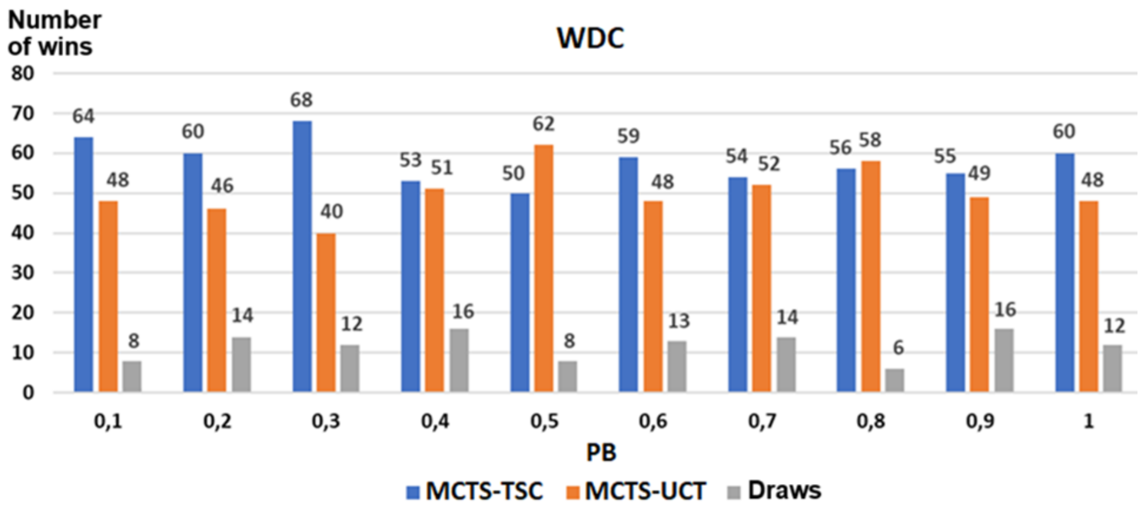

Fig. 1. Results of playing a set of games of the MCTS-TSC and MCTS-UCT players when MCTS-TSC used tree shape controlling by the *WDC* criterion

According to the results shown in the diagram in Fig. 1, the following observations can be made:

1. A significant positive effect was obtained in increasing the "strength" of the MCTS-TSC player compared to the MCTS-UCT player in some cases. This effect is observed when the MCTS-TSC player was given a predefined desired (reference) tree shape, which the tree takes after executing 10%, 20%, and 30% (*PB* = 0.1, 0.2, 0.3) of the computational budget. That approved an increase in search efficiency when using the *WDC* criterion for controlling the shape of the search tree. Also, a good positive effect was obtained with the parameter values *PB* = 0.6 and *PB* = 1.

2. The best positive effect was observed in the following cases. During a non-big initial part (10%–30%) of the search iteration budget, tree construction process was directed to building a wider shape of the search tree. Next the process was directed towards deepening the tree shape compared to the tree built by the standard MCTS-UCT technique. When setting the parameter value *PB* = 0.1 (10%), the MCTS-TSC player won 33.3% more games than the MCTS-UCT player. At *PB* = 0.2 (20%) – 30.4% more games won, and the largest positive effect was obtained at *PB* = 0.3 (30%) – 70% more games won.

3. Besides, MCTS-TSC player won 22.9% more games at *PB* = 0.6 and 25% more games at *PB* = 1. Obtaining such a good positive effect also with these desired shapes of the search tree indicates the next: for a certain application task (in this case, the Connect Four game) there may be not only one, but also several typical shapes of the search tree, setting of which increases the search efficiency.

As conclusion to this part of the experiments it might be noted that there were obtained new results, which approve that MCTS-TSC technique with usage of the *WDC* criterion is able to overcome the MCTS method. That is to increase strength of the MCTS-TSC player comparing to the MCTS-UCT for some shapes of the search tree.

5.2. Results of the experiments of the *DWC* criterion

A sets of Connect Four games was played to test the MCTS-TSC technique compared to the standard MCTS-UCT technique when the *DWC* tree shape control criteria was used.

The games with usage of the *DWC* criterion were done according to the same scheme as with usage of the *WDC* criterion. The obtained values were used to construct a summary comparative diagram of the results shown in the Figure № 2.

The symbols and colors in the Figure№ 2 have the same meaning as in the Figure № 1.

According to the results shown in the diagram in Fig. 2, the following observations can be made:

1. The general picture of the results of the execution of the same set of experimental games when using the *DWC* search tree shape control criterion turned out to be similar.

2. In contrast to the application of the *WDC* criterion, when using the *DWC* criterion, the greatest positive effect of tree shape control was observed at values of the *PB* parameter by 0.1 larger

(*PB* = 0.2, 0.3, 0.4, 0.7). But the greatest positive effect was obtained in the same way as for the *WDC* criterion, at the value *PB* = 0.3 (30%). Also, in the same way as for the *WDC* criterion, the positive effect was observed at *PB* = 1.

3. The first and the widest range of the MCTS-TSC efficiency was obtained at *PB* values from 0.2 to 0.4. When setting the parameter value *PB* = 0.2 (20%), the MCTS-TSC player won 19.2% more games than the MCTS-UCT player, at *PB* = 0.3 (30%) – 52.3% more games won, at *PB* = 0.4 (40%) – 24% more games won.

4. Positive effect was obtained in two cases more. At the parameter value *PB* = 0.7, the MCTS-TSC player won 29.2% more games, and at *PB* = 1, the games won were 26.5% more.

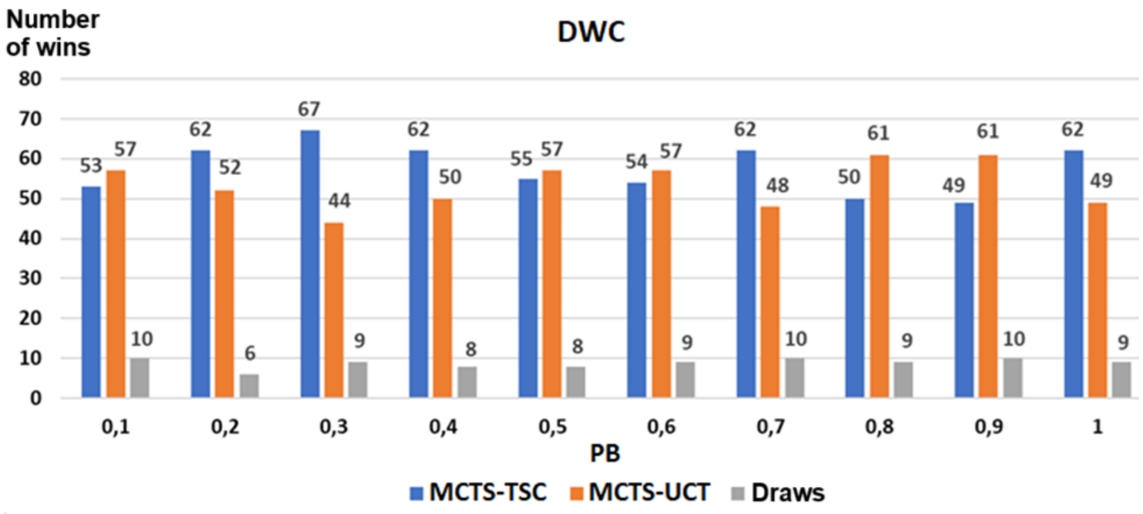

Fig. 2. Results of playing a set of games of the MCTS-TSC and MCTS-UCT players when MCTS-TSC used tree shape controlling by the *DWC* criterion

As conclusion to this part of the experiments it might be noted that there were obtained new results, which approve that MCTS-TSC technique with usage of the *DWC* criterion is able to overcome the MCTS method. That is to increase strength of the MCTS-TSC player comparing to the MCTS-UCT for some shapes of the search tree.

6. Discussion of the *DWC* and *WDC* criteria study

The following should be noted:

1. The results of the experiments confirmed the hypothesis of the proposed MCTS-TSC technique for further development of the MCTS search method. The hypothesis is that controlling the process of constructing the MCTS tree and directing this process to construct a tree with a more typical shape for a particular applied task (game) increases the efficiency of the MCTS search method. That means the strength of the player using the MCTS-TSC technique with control of the search tree shape increases as well.

2. For the Connect Four game it turned out that the shape with setting parameter *PB* = 0.3 was the best desired (typical) shape of the search tree. If MCTS-TSC will try to direct the tree construction process to this shape (first expand, then deepen) then search efficiency and strength of the player is improved. I.e. this is the shape which the search tree has after executing 30% of the budget of iterations.

3. Influence of the parameters values of the *WDC* and *DWC* criteria formulas on the search efficiency depend to some extent on the specific application task (game). This means that for different application tasks the values of the C_{WD} and C_{DW} parameters, at which a positive effect of the MCTS-TSC technique is observed, may also differ. For example, these values may differ from values that were determined for the Connect Four game. In addition, the values of the efficiency ranges of other search tuning parameters of the MCTS-TSC with tree shape control may also differ, as well as the width of these ranges.

4. Experimental verification of the proposed criteria and the MCTS-TSC technique on other applied tasks and games may be proposed as the direction for further research.

7. Conclusion

When *WDC* criterion was used, the MCTS-TSC player won from 30% to 70% more games than the MCTS-UCT player for some search tree shapes.

When *DWC* criterion was used, the MCTS-TSC player won from 19% to 52% more games than the MCTS-UCT player for some search tree shapes.

I.e., when establishing certain desired (reference) tree shapes, the use of both criteria for controlling the search tree shape (*WDC* and *DWC*) increased the efficiency of searching for the best further game moves. That means that both of these criteria increased the strength of the player, which used the proposed MCTS-TSC search technique with control of the tree shape, compared to the player using the standard MCTS-UCT search technique.

So, ability of the both proposed *WDC* and *DWC* criteria of the proposed MCTS-TSC technique to improve the MCTS method was approved. That means that with a successful selection of the *WDC* and *DWC* formula's parameters for selecting the next branch of the search tree MCTS-TSC technique allows to bring positive effect.

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АПРОБАЦІЯ КРИТЕРІЇВ ТИПУ ГЛИБИНА-ШИРИНА ДЛЯ КОНТРОЛЮ ФОРМИ ДЕРЕВА ДЛЯ ПОШУКУ В ДЕРЕВІ МЕТОДОМ МОНТЕ КАРЛО

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Ця стаття присвячена науковій проблемі вдосконалення пошуку по дереву методом Монте-Карло (*Monte Carlo Tree Search, MCTS*). Об'єктом дослідження є процес виконання пошуку по дереву за допомогою *MCTS*. Предметом дослідження є спосіб вдосконалення *MCST* з керуванням формою дерева пошуку шляхом використання раніше запропонованих авторами критеріїв *DWC* (*Depth/Width Criterion*) та *WDC* (*Width/Depth Criterion*). Цей спосіб отримав назву *MCTS-TSC* (*Monte Carlo Tree Search with Tree Shape Control*). Методи дослідження базуються на теорії структур даних і методах аналізу.

Метою роботи є проведення розширеної експериментальної апробації способу *MCTS-TSC*, що вдосконалює метод *MCTS*. Зокрема, мета полягає у підтвердженні того, що критерії контролю форми дерева *DWC* і *WDC* забезпечують вибір кращого ходу та збільшення сили гравця порівняно зі стандартним способом реалізації методу *MCTS – MCTS-UCT* (*Monte Carlo Tree Search with Upper Confidence bounds applied to Trees*).

Для досягнення мети були поставлені наступні завдання: згідно з розробленою методикою апробації провести серію експериментів для підтвердження, що критерій *WDC* способу *MCTS-TSC* здатен вдосконалити пошук методом *MCTS*; згідно з розробленою методикою апробації провести серію експериментів для підтвердження, що критерій *DWC* способу *MCTS-TSC* здатен вдосконалити пошук методом *MCTS*.

Обидва критерії, *WDC* та *DWC*, способу *MCTS-TSC* були протестовані на серії партій гри *Connect Four* між гравцем, який використовував спосіб *MCTS-TSC*, і гравцем, який використовував спосіб *MCTS-UCT*. В експериментах були використані різні параметри налаштування формул критеріїв *WDC* і *DWC* способу *MCTS-TSC*.

У статті описана методика апробації способу *MCTS-TSC* порівняно зі способом *MCTS-UCT*, а також виконаний порівняльний аналіз результатів експериментів. Для деяких форм дерева пошуку, у випадку використання критерію *WDC*, гравець *MCTS-TSC* виграв від 30% до 70% більше ігор, ніж гравець *MCTS-UCT*, і виграв від 19% до 52% більше ігор у випадку використання критерію *DWC*. Отже, ефективність запропонованого способу *MCTS-TSC* для вдосконалення методу *MCTS* була підтверджена для обох критеріїв *WDC* і *DWC*.

Ключові слова: критерії типу глибина-ширина, пошук в дереві методом Монте-Карло, *MCTS*, *MCTS-UCT*, *MCTS-TSC*, контроль форми дерева пошуку.