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AN IMPLICIT UPWIND DIFFERENCE SCHEME FOR THE BOUNDARY CONTROL PROBLEM OF HYPERBOLIC SYSTEMS

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1. Introduction. In many applications of hyperbolic balance laws (open-channel flow, gas transport networks), the boundary conditions are not passive but include a control or perturbation term, through which the system is actuated from outside. For the uncontrolled problem, an explicit upwind scheme can be used, but its stability is subject to the Courant–Friedrichs–Lewy (CFL) restriction, which becomes prohibitive when the spatial mesh is fine relative to the admissible time step. This motivates the construction of an *implicit* upwind scheme for the boundary-controlled problem, free of a CFL-type mesh restriction. This thesis presents the statement of the boundary control problem for a linear symmetric t-hyperbolic system with variable coefficients and the construction of such an implicit scheme; its stability analysis is presented in a companion thesis.

2. Statement of the boundary control problem. Let the characteristic speeds $a_i(x)$, $i = 1, \dots, n$, depend on the spatial variable x. Consider the linear symmetric t-hyperbolic system

$$\frac{\partial \mathbf{v}}{\partial t} + K(x)\frac{\partial \mathbf{v}}{\partial x} + Q(x)\mathbf{v} = 0,$$

(1) where

$$K(x) = \operatorname{diag}\{K^+(x), -K^-(x)\}, \quad K^+(x) = \operatorname{diag}\{a_1(x), \dots, a_m(x)\}, \quad K^-(x) = \operatorname{diag}\{a_{m+1}(x), \dots, a_n(x)\},$$

(2) with $a_i \in C^1([0,l])$, $a_i(x) > 0$ for all i and $x \in [0,l]$, and $Q(x) = \operatorname{diag}\{q_1(x), \dots, q_n(x)\}$ is a given diagonal matrix with $q_i \in C^0([0,l])$.

Equation (1) is supplemented with canonical boundary conditions containing control (perturbation) terms $\psi^I(t)$, $\psi^{II}(t)$: at $x = 0$,

$$\mathbf{v}^I = s\,\mathbf{v}^{II} + \psi^I(t), \qquad t \in [0, \infty),$$

(3) and at $x = l$,

$$\mathbf{v}^{II} = r\,\mathbf{v}^I + \psi^{II}(t), \qquad t \in [0, \infty),$$

(4) where $\mathbf{v}^I = (v_1, \dots, v_m)^T$, $\mathbf{v}^{II} = (v_{m+1}, \dots, v_n)^T$, s is a constant $m \times (n-m)$ matrix, r is a constant $(n-m) \times m$ matrix, and ψ^I, ψ^{II} have continuous components. The initial condition is

$$\mathbf{v}(x,0) = \mathbf{v}_0(x), \qquad x \in (0,l),$$

(5) with $\mathbf{v}_0 \in L^2\big((0,l),\mathbb{R}^n\big)$. It is assumed that $\mathbf{v}_0$ and $\psi^I(0), \psi^{II}(0)$ satisfy the compatibility conditions induced by (3)–(4) at $t = 0$.

Problem. *Construct a finite-difference scheme for problem (1), (3)–(5) that is free of a CFL-type mesh restriction, i.e. whose stability does not require any relation between the spatial step Δx and the time step Δt.*

3. Construction of the implicit upwind scheme. On the mesh $G_h = \{(t^\kappa, x_j) : \kappa = 0, \dots, K;\ j = 0, \dots, J\}$, $t^\kappa = \kappa\Delta t$, $x_j = j\Delta x$, $J\Delta x = l$, $K\Delta t = T$, let $(v_i)_j^\kappa \approx v_i(t^\kappa, x_j)$. Unlike the explicit scheme for the uncontrolled problem, the spatial difference here is evaluated at the *new* time level $\kappa + 1$:

$$(v_i)_j^{\kappa+1} = (v_i)_j^\kappa - (a_i)_j \frac{\Delta t}{\Delta x}\left[(v_i)_j^{\kappa+1} - (v_i)_{j-1}^{\kappa+1}\right] - \Delta t\, q_j (v_i)_j^{\kappa+1}, \qquad i \le m,$$

(6)

$$(v_i)_j^{\kappa+1} = (v_i)_j^\kappa - (a_i)_j \frac{\Delta t}{\Delta x}\left[(v_i)_{j+1}^{\kappa+1} - (v_i)_j^{\kappa+1}\right] - \Delta t\, q_j (v_i)_j^{\kappa+1}, \qquad i > m,$$

(7) for $j = 1, \dots, J-1$, $\kappa = 0, \dots, K-1$, with initial data $(v_i)_j^0 = (\varphi_i)_j$. Because (6)–(7) involve the unknown values at time level $\kappa + 1$ on both sides, at every time step a linear algebraic system must be solved for $\{(v_i)_j^{\kappa+1}\}$; in return, no restriction of CFL type on $\Delta t/\Delta x$ is required for the construction of the scheme, which is the principal motivation for this discretization.

The control boundary conditions (3)–(4) are approximated to first order by extending the ghost values $(v_i)_0^{\kappa+1}$ $(i > m)$ and $(v_i)_J^{\kappa+1}$ $(i \le m)$, which do not appear in (6)–(7), by their nearest interior neighbors, $(v_i)_0^{\kappa+1} := (v_i)_1^{\kappa+1}$ $(i > m)$ and $(v_i)_J^{\kappa+1} := (v_i)_{J-1}^{\kappa+1}$ $(i \le m)$. Substituting these into (3)–(4) yields the discrete boundary conditions

$$(\mathbf{v}^I)_0^{\kappa+1} = s(\mathbf{v}^{II})_1^{\kappa+1} + (\psi^I)^{\kappa+1}, \qquad (\mathbf{v}^{II})_J^{\kappa+1} = r(\mathbf{v}^I)_{J-1}^{\kappa+1} + (\psi^{II})^{\kappa+1}, \qquad \kappa = 0, \dots, K-1.$$

(8) Scheme (6)–(8), together with the initial data, constitutes a well-defined implicit finite-difference approximation of the boundary control problem (1), (3)–(5), of first order in Δt and Δx.

4. Discussion. The implicit scheme (6)–(8) differs from the explicit upwind scheme used for the uncontrolled problem in two respects: (i) the transport term is discretized at the new time level, which requires solving a linear system (triangular, by the upwind ordering, within each characteristic block) at every step; (ii) stability of the scheme is not conditioned on a relation between Δt and Δx, which makes it preferable when the spatial resolution required by the model is much finer than the temporal

resolution needed to resolve the boundary control signal — a situation that is common, for instance, in the numerical simulation of open-channel hydraulic networks. The price of this unconditional applicability is the need, at each time step, to solve a linear system instead of updating the solution by an explicit formula; however, due to the upwind structure of (6)–(7), this system is lower (respectively, upper) triangular within each of the two characteristic blocks and can be solved by a single sweep, at a computational cost comparable to that of the explicit scheme per time step.

The question of whether the numerical solution of (6)–(8) reproduces the exponential stability, in the sense of Lyapunov, that is expected of the boundary control problem (1), (3)–(5) under a dissipativity condition on the control parameters (s, r) is addressed in a companion thesis, by means of a discrete Lyapunov function adapted to the implicit scheme.

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TABLE OF CONTENTS

1.	**Гелдибаев Бегенч Егендурдыевич**, ОБЗОР ИССЛЕДОВАНИЙ VISION-LANGUAGE MODELS ДЛЯ ЗАДАЧ ВИЗУАЛЬНОГО РАСПОЗНАВАНИЯ	**5**
2.	**Ergashov Ziyodullo Bobir og'li**, O‘ZBEKISTON HUDUDIDA QADIMGI SIVILIZATSIYALARNING SHAKLLANISHI	**10**
3.	**L.K. Jamolova, H.Sh.Sharifov**, FACTORS AFFECTING THE EFFICIENCY OF SOLAR PANELS	**15**
4.	**X.R. G‘afforov**, DIAGNOSIS OF THE LEVEL OF FORMATION OF PROFESSIONAL COMPETENCIES OF STUDENTS OF TECHNICAL HIGHER EDUCATION INSTITUTIONS	**18**
5.	**Sag‘dullayeva Zuhra Ne’matulla qizi**, KOMPENSATSIYAVIY YONDASHUV ASOSIDA OLIY TA’LIM MUASSASALARIDA FRANSUZ TILINI O‘QITISH METODIKASI	**22**
6.	**Astanakulov Ulugbek Khusanovich**, PEDAGOGICAL APPROACHES TO TEACHING WRITING IN EFL: A COMPARATIVE THEORETICAL ANALYSIS	**28**
7.	**Нуруллаева Фарангиз Толибжон кизи**, КОГНИТИВНО-СЕМАНТИЧЕСКИЕ МЕХАНИЗМЫ КОНЦЕПТУАЛЬНОЙ МЕТАФОРЫ В СОВРЕМЕННОМ РУССКОМ ЯЗЫКЕ	**32**
8.	**Zikirullayeva Nilufar Dilmurod kizi**, THE IMPORTANCE OF GREEN ECONOMY IN WORLD ECONOMIC DEVELOPMENT	**35**
9.	**Mansurova Rayxona Adham qizi, S. Chimpo‘latova**, XX ASR MISR ADABIYOTINING YIRIK NAMOYANDASI YOZUVCHI YAHYO HAQQINING HAYOTI VA IJODI	**40**
10.	**Abdiqodirova O'g`iloy Abdirayim qizi**, RAQAMLI TA’LIM TEXNOLOGIYALARI YORDAMIDA TALABALARDA MUSTAQIL TA’LIM KO‘NIKMALARINI RIVOJLANTIRISHNING PEDAGOGIK ASOSLARI	**44**
11.	**Kodirova Dilfuza**, SATIRICAL ELEMENTS IN THE POLITICAL AND SOCIAL CRITICISM OF JONATHAN SWIFT	**49**
12.	**Meliyeva Sevara Faxriddin qizi**, THE CONNOTATIVE FIELD OF SUBSTANDARD UNITS IN UZBEK AND ENGLISH	**52**
13.	**Муратбаева Азиза Даулетбаевна**, СПОСОБЫ И МОДЕЛИ ОККАЗИОНАЛЬНЫХ ПРЕОБРАЗОВАНИЙ В ПЕРИОДИЧЕСКОЙ ПЕЧАТИ	**57**
14.	**Rustamov Akbar Askarovich**, TAKING INTO ACCOUNT THE AGE-RELATED CHARACTERISTICS OF 6–7-YEAR-OLD CHILDREN IN THE PROCESS OF INDIVIDUALIZED CHESS INSTRUCTION	**62**
15.	**Махамадалиева Н.Р., Хамидуллаева Ф.И., Бабаджанова Н.Т.**, ЦИТОКИНОВЫЙ ПРОФИЛЬ СМЕШАННОЙ СЛЮНЫ КАК	**70**

	МАРКЕР РИСКА РАЗВИТИЯ ГИНГИВИТА У ПОДРОСТКОВ ПОСЛЕ ПЕРЕНЕСЁННОЙ COVID-19 ИНФЕКЦИИ	
16.	**Salimov Nurali Ramazon o`g`li**, O‘ZBEKISTONDA SUN`IY INTELLEKT TEXNOLOGIYALARIDAN FOYDALANGAN HOLDA KIBERXAVFSIZLIKNI RIVOJLANTIRISH ISTIQBOLLARI	**73**
17.	**Muxammedova Dilshoda Nodir qizi**, PUBLITSISTIK USLUBDA QO‘LLANUVCHI TOPONIMIK PERIFRAZALARNING SINONIMIK XUSUSIYATLARI	**78**
18.	**Safoyev Nodirjon Nematjon o‘g‘li**, O‘ZBEK TILIDAGI AVTOMATIK TARJIMA SIFATINI OSHIRISH UCHUN TAKOMILLASHTIRILGAN BERT YONDASHUVLARI	**84**
19.	**Mustafayeva Matlubaxon Ilhomjon qizi**, SPECIFIC FEATURES OF IDIOMS IN ENGLISH AND RUSSIAN LITERARY TEXTS	**88**
20.	**Умаров Бобурбек Носир угли, Жураев Ахтам Хамроевич**, ИССЛЕДОВАНИЕ ОСНОВНЫХ ПОКАЗАТЕЛЕЙ ВЕРМИКУЛИТА В КАЧЕСТВЕ АДСОРБЕНТА	**93**
21.	**Нуров С.С., Мусаев А.Х.**, МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ГАЗОПЕРЕКАЧИВАЮЩЕГО АГРЕГАТА ДЛЯ СИНТЕЗА СИСТЕМЫ АВТОМАТИЧЕСКОГО УПРАВЛЕНИЯ В СРЕДЕ MATLAB/SIMULINK	**95**
22.	**Nazarov Alimardan Kamol o’g’li**, OTA-ONA VA O‘SMIR MUNOSABATLARINI O’GANISHGA OID METODIKALARINING ILMIY ASOSLARI	**100**
23.	**Hamidova Nozima Sirojiddin qizi, Temirova Matlab Ibodovna**, ISHLATILGAN O‘SIMLIK YOG‘LARINI QAYTA ISHLASH ORQALI QO‘SHIMCHA QIYMATLI MAHSULOTLAR OLISHNING TEXNOLOGIK IMKONIYATLARI	**102**
24.	**Azamat Orunbayev**, THE EFFECTS OF AEROBIC-STEP AND PILATES EXERCISES ON STRENGTH, FLEXIBILITY, ANAEROBIC POWER, BALANCE, AND BODY COMPOSITION	**106**
25.	**Saminbayev Mashhurbek Ravshanbek o‘g‘li, Qobulov Boburmirzo Ulug‘bek o‘g‘li**, ANIME YOSHLAR DUNYOQARASHIDA O‘LIM VA HAYOT FALSAFASINING TRANSFORMATSIYASI	**112**
26.	**Yuldasheva Sevara Bakhodir kizi**, THE SPECIFIC FEATURES OF THE OGHUZ LANGUAGE IN WRITTEN MONUMENTS OF THE 11TH-12TH CENTURIES	**116**
27.	**Журакулов Санжар**, КРИТЕРИИ И ПОКАЗАТЕЛИ ОЦЕНКИ ЭФФЕКТИВНОСТИ САМОСТОЯТЕЛЬНОГО ОБУЧЕНИЯ ФИЗИКЕ СТУДЕНТОВ ТЕХНИЧЕСКИХ НАПРАВЛЕНИЙ НА ОСНОВЕ ЦИФРОВЫХ ТЕХНОЛОГИЙ	**121**
28.	**Yuldoshov Elchinbek Qosim ugli, Khayitov A.A.**, DISPENSARY EXAMINATION FOR ENT DISEASES	**124**

29.	**Nuraliyev Islom Saidaliyevich**, BO‘LAJAK O‘QITUVCHILARDA TESTOLOGIK KOMPETENTLIKNI RIVOJLANTIRISHNING AMALIY HOLATI VA XORIJIY TAJRIBANING QIYOSIY-PEDAGOGIK TAHLILI	**129**
30.	**Qazoqov Jo‘rabek Roziqovich, Uvayzov Saidjon Komilovich, Mizomov Muhammad Saydulla o`g`li**, OPERATOR INTERFEYSLARINI ISHLAB CHIQISHDA ERGONOMIK YONDASHUVLAR	**135**
31.	**Maxkamova Xilolaxon Xasanxon qizi**, FORUM FOCUSED INSTROCTION IN COMUNICATIVE ENGLISH CLASSES: BENEFITS AND LIMITATIONS	**139**
32.	**Boboyeva Zebo Hasanovna**, OLIY TA'LIM TIZIMIDA PEDAGOGIK MADANIYATNI SHAKLLANTIRISHNING INNOVATSION YONDASHUVLARI	**142**
33.	**Yarasheva Dilnoza Ismoil qizi**, METHODOLOGY FOR DETERMINING FLEXIBILITY IN FEMALE HANDBALL PLAYERS	**147**
34.	**Serikbayeva Dina Altinbayeva**, BOSHLANG‘ICH SINFLARDA MATEMATIK TAFAKKURNI RIVOJLANTIRISHDA INNOVATSION YONDASHUVLAR	**151**
35.	**Atamurodova Guljon Komilovna, Abdullayeva Maryambibi Jumaniyazovna**, TALABALARDA IJTIMOIY FAOLLIKNI INNOVATSION PEDAGOGIK TEXNOLOGIYALAR ASOSIDA RIVOJLANTIRISHNING METODIKASI	**155**
36.	**Abdullayva Mohlaroyim Nodirbek qizi, Rustamova Fotima Umidjon qizi, Rustamova Zuhra Umidjon qizi**, THE INFLUENCE OF DIET ON OVULATORY FUNCTION IN WOMEN AFTER OVARIAN CAUTERIZATION: A LITERATURE REVIEW	**159**
37.	**Kuchkarov Anvarbek Shermirzayevich**, SCIENTIFIC AND PEDAGOGICAL FOUNDATIONS FOR IMPROVING PHYSICAL EDUCATION AND SPORTS PEDAGOGY IN THE CONTEXT OF DIGITAL TRANSFORMATION	**163**
38.	**Ne’matjonov Turg‘unpo‘lat Shokirjon o‘g‘li**, ANALYSIS OF HISTORICAL TOPONYMS IN THE BABURNAMA	**168**
39.	**Mamatov Axadbek**, BUXORO VOHASIDA NAQSHBANDIYLIK TA'LIMOTINING SHAKLLANISH BOSQICHLARI	**171**
40.	**To‘rayeva Charosxon Shavkat qizi**, MAKTABGACHA YOSHDAGI BOLALARNING INTELLEKTUAL RIVOJLANISHIDA MONTESSORI METODIKASINING SAMARADORLIGI	**177**
41.	**Tosheva Kamola Komiljon qizi**, TRAINING LOAD PLANNING FOR HIGHLY SKILLED FEMALE WEIGHTLIFTERS	**183**

42.	**Khamraeva Zamira, Razhabov Rustam, Khovaylo Vladimir**, MAGNETIC PROPERTIES AND ELECTRICAL RESISTIVITY OF FE(NI)-MN-AL MELT-SPUN RIBBONS	**189**
43.	**Sirojev Shoxrux Fayzullo o‘g‘li**, THE ROLE OF VOLLEYBALL IN DEVELOPING PHYSICAL AND PSYCHOLOGICAL READINESS	**191**
44.	**Otabek Turlibekov , Oliy Akhmedov , Avazbek Taniberdiyev**, SYNTHESIS, PROPERTIES AND POTENTIAL APPLICATIONS OF QUATERNARY AMMONIUM DERIVATIVES OF CHITOSAN OBTAINED FROM PLEUROTUS OSTREATUS	**194**
45.	**Курамбаева Дилафруз Шаукатовна**, ОБРАЗ УМАЙ В МИФОЛОГИЧЕСКИХ ПРЕДСТАВЛЕНИЯХ КАРАКАЛПАКОВ	**202**
46.	**Keldibekov Jahongir Vali o'g'li**, XOSMAS INTEGRALLAR KONVERGENTLIGINING YANGI SHARTLARI HAMDA ULARNING DIFFERENSIAL TENGLAMALAR MODELLARIGA TATBIQI	**207**
47.	**Sharipov J.R.**, BILATERAL VERTEBRAL ARTERY HEMODYNAMIC RESPONSE IN ARTERIAL HYPERTENSION COMPLICATED BY ISCHEMIC HEART DISEASE	**212**
48.	**N.B. Saidmurodova , G.U. Lutfullaev**, MICROBIOLOGICAL CHARACTERISTICS OF THE NASAL MUCOSA IN PATIENTS WITH CHRONIC SUBATROPHIC RHINITIS ASSOCIATED WITH TYPE 2 DIABETES MELLITUS	**215**
49.	**Narbayeva Sofiya Murod qizi**, SUN'IY INTELLEKTGA ASOSLANGAN PEDAGOGIK TEXNOLOGIYALAR ORQALI OLIY TA'LIMDA TALABALARNING AKADEMIK MUVAFFAQIYATINI OSHIRISH	**225**
50.	**Sattarova Muhabbat Alijanovna**, DEVELOPING THE CREATIVE POTENTIAL OF STUDENTS IN PEDAGOGY PROGRAMS	**230**
51.	**Sattarova Muhabbat Alijanovna**, MENTORSHIP MODEL FOR WORKING WITH GIFTED STUDENTS	**232**
52.	**Sattarova Muhabbat Alijanovna**, STRUCTURAL COMPONENTS OF AN INNOVATIVE PEDAGOGICAL MODEL	**235**
53.	**Sodiqova Vazira Yaxyoqul qizi**, CURVATURE CORRESPONDING TO A SQUARE: DEFINITION AND GEOMETRIC MEANING	**237**
54.	**Xoldarova Dilfuza Komiljon qizi**, MUAMMOLI TA’LIM ASOSIDA KOGNITIV VA METAKOGNITIV O‘ZLASHTIRISH TEXNOLOGIYALARINING O‘ZIGA XOS JIHATLARI	**240**
55.	**Dusmurodova Muhayyo Faxritdin qizi**, TA’LIM JARAYONIDA SHAXSIYLASHTIRILGAN O‘QITISH ORQALI SHAXS RIVOJLANISHINI TA’MINLASH USULLARI	**247**
56.	**Jumaboyev Azizjon Sayfiddin o‘g’li**, SAMARQAND O‘LKASHUNOSLIK JAMIYATLARI FAOLIYATIDA MADANIY	**253**

	MEROSNI ASRASH MUAMMOLARI (XX ASRNING 20–80-YILLARI)	
57.	**Файзиев М.М.**, МАТЕМАТИК РЕЖАЛАШТИРИШ АСОСИДА МАРКАЗДАН ҚОЧМА КУЧ ТАЪСИРИДА ЮҚОРИ ЭКСПЛУАТАЦИОН ХУСУСИЯТЛАРГА ЭГА БЎЛГАН АНИЗОТРОП СТРУКТУРАЛИ ЦИЛИНДРСИМОН ФИЛЬТРЛАР ОЛИШ ТЕХНОЛОГИЯСИНИНГ ОПТИМАЛ ПАРАМЕТРЛАРИНИ АНИҚЛАШ	**256**
58.	**Бабажанова Навбахор**, “ПСИХОЛОГИЧЕСКАЯ ПРИРОДА ОБРАЗА «ЛИШНЕГО ЧЕЛОВЕКА” В РОМАНЕ И. С. ТУРГЕНЕВА “ДНЕВНИК ЛИШНЕГО ЧЕЛОВЕКА”	**260**
59.	**Абдурахимова Зарнигора Бахтийор кизи, Абдураимова Н.Р.**, РОЛЬ ОБРАЗОВАНИЯ И ПРОФЕССИОНАЛЬНОЙ ПЕРЕПОДГОТОВКИ ЖЕНЩИН В УСЛОВИЯХ РАЗВИТИЯ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА	**262**
60.	**Sultonov Bobirxon Muhammadxonovich**, FUQAROLIK HUQUQIDA MAJBURIYATLARNING BAJARILISHINI TA'MINLASHNING O'ZIGA XOS XUSUSIYATLARI	**267**
61.	**Akramov Ibrohimjon Oxunjon o‘g‘li**, OILAVIY MUNOSABATLARDA TENG HUQUQLILIK PRINSIPI HUQUQIY MAZMUNI	**270**
62.	**М.М. Файзиев**, ПЛАСТМАССА МАҲСУЛОТЛАРИНИ ИШЛАБ ЧИҚАРИШ ЖАРАЁНИДА МОЙДАН ҚАТТИҚ ЗАРРАЧАЛАРНИ АЖРАТИБ ОЛИШ УЧУН ФИЛЬТР ЭЛЕМЕНТЛАРИНИ ОЛИШ ТЕХНОЛОГИЯСИ	**274**
63.	**Turaev Ahmed Kholmominovich**, DIRECTIONS THAT INFLUENCE THE FORMATION OF TESTOLOGICAL COMPETENCE	**277**
64.	**Ixtiyor G‘aniyevich Jalilov**, THE HISTORICAL EXPERIENCE OF THE MAHALLA INSTITUTION AND PUBLIC OVERSIGHT IN SOUTHERN UZBEKISTAN	**280**
65.	**Ixtiyor G‘aniyevich Jalilov**, FACTORS INFLUENCING THE DEVELOPMENT OF FAMILY ENTREPRENEURSHIP IN THE MAHALLAS OF SOUTHERN UZBEKISTAN	**285**
66.	**Yuldashev G‘ulomjon, Qosimov Bekzod Ulug‘bek o‘g‘li**, KARKIDON SUV OMBORI ATROFI TUPROQ PROFILIDA TUZLAR REJIMI VA MIKROELEMENTLARNING RADIAL-LATERAL DIFFERENSIATSIYASI	**289**
67.	**Kamol Akbarov,** KARKIDON SUV OMBORI ATROFI TUPROQ PROFILIDA TUZLAR REJIMI VA MIKROELEMENTLARNING RADIAL-LATERAL DIFFERENSIATSIYASI	**295**
68.	**Jo’rabekova Gulshoda,** KOGNITIV USLUBNING YOSHGA BOG’LIQ XUSUSIYATLARI	**298**

69.	**Sharobiddinova Gulshodaxon Rustamjon qizi,** IKKI O'LCHOVLI SIMPLEKSDAGI ALMASHTIRILGAN VOLTERRA OPERATORLARINING DINAMIKASI HAQIDA	**301**
70.	**Аминова Моҳирахон Мўминжон қизи,** СОЗДАНИЕ ХИМИЧЕСКИХ ПРЕПАРАТОВ ДЛЯ ЗАЩИТЫ СЕЛЬСКОХОЗЯЙСТВЕННЫХ КУЛЬТУР НА ОСНОВЕ ПРОМЫШЛЕННЫХ ОТХОДОВ И ИХ ПРИМЕНЕНИЕ	**304**
71.	**Rakhmanova Nozimakhon Ibrokhimjon qizi,** NATIONAL-CULTURAL UNITS IN ENGLISH AND UZBEK: A CROSS-LEVEL COMPARATIVE ANALYSIS OF THEIR SEMANTIC, LINGUOCULTURAL, AND PRAGMATIC FEATURES ABSTRACT	**307**
72.	**Dehqonova Shahnoza Anvar qizi,** MAKTABGACHA TA'LIM TASHKILOTI RAHBARINING BOSHQARUV KOMPETENSIYASINI RIVOJLANTIRISH: ZAMONAVIY YONDASHUVLAR VA SAMARALI MEXANIZMLAR	**320**
73.	**Feruz Yuldashev,** ENTREPRENEURIAL DEVELOPMENT OF HIGHER EDUCATION INSTITUTIONS IN UZBEKISTAN: COMPARATIVE EVIDENCE FROM PUBLIC AND PRIVATE UNIVERSITIES	**325**
74.	**Nurullayev Mirxon Muhammadovich,** AGENTLI SUN'IY INTELLEKT TIZIMLARIDA AXBOROT OQIMI XAVFSIZLIGIGA TAHDIDLAR TASNIFI VA HIMOYALASH USULLARINING QIYOSIY TAHLILI	**329**
75.	**Soibov Johongir Ergash o`g`li,** HUDUDIY ISHLAB CHIQARISH MAJMUALARINI SAMARALI ENERGIYA BILAN TA'MINLASH SXEMALARINI TANLASH MASALALARI	**335**
76.	**Shukurova Ozoda Odil qizi,** RAQAMLI PLATFORMALARDA XIZMAT KO'RSATISH SHARTNOMALARINING ELEKTRON SHAKLI VA UNI TASDIQLASH MUAMMOLARI	**337**
77.	**Qosimov Oybek Abdumannon o'g'li,** PAST INERSIYALI ENERGIYA TIZIMLARIDA GIBRID SHAMOL-QUYOSH ELEKTR STANSIYALARINING CHASTOTA BARQARORLIGIGA TA'SIRINI BAHOLASH	**341**
78.	**Teshaboyev Rivojiddin Ibrohimjon o'g'li,** KUCH TRANSFORMATORLARIDA ENERGIYA ISROFLARI VA ULARNI KAMAYTIRISH USULLARI	**346**
79.	**Ergasheva Zilola Ko'paysin qizi,** MUSIQIY-DIDAKTIK O'YINLAR VOSITASIDA MAKTABGACHA YOSHDAGI BOLALARNING MUSIQIY QOBILIYATLARINI RIVOJLANTIRISH METODIKASI	**348**
80.	**To`lqinova Gulsanam Bahtiyor qizi,** TEMIR-BETON KONSTRUKSIYALARNING ZILZILABARDOSHLIGINI OSHIRISHNING ZAMONAVIY, AMALIY USULLARI	**354**

81.	**To‘xtaraliyev Sohibjon Murodjon o‘g‘li, Xolmatov Dilshod Sottorjonovich,** TEXNOLOGIK CHANG XOSSALARINI TAVSIFLASH VA CHANG TOZALASH QURILMASI SINOVLARINI METODIK ASOSLASH	**358**
82.	**G`oziyev Islomjon Ravshanovich, N.N.Umaraliyev,** GAZ GENERATORI REAKSIYA ZONASIDAGI HARORATNI MASOFADAN O‘LCHASH VA MONITORING QILISH TIZIMINI YARATISH	**362**
83.	**Xudoynazarova Nodira Shaydullayevna,** O‘ZBEKISTONDA HUDUDIY (SHAHAR VA QISHLOQ) AYOLLARINING TADBIRKORLIK IDENTIKLIGI VA MOTIVATSION SOHASI QIYOSIY TAHLILI	**366**
84.	**Бобобекова Шохисита Хоззиржон кизи,** МЕТОДИЧЕСКИЕ ОСНОВЫ ПЕРСОНАЛИЗАЦИИ ОБУЧЕНИЯ В ЦИФРОВОЙ ОБРАЗОВАТЕЛЬНОЙ СРЕДЕ ОБЩЕОБРАЗОВАТЕЛЬНОЙ ШКОЛЫ	**369**
85.	**Berdiyorova Mohira Nurali qizi,** MAHALLIY MINERAL QO‘SHIMCHALAR ASOSIDA GIPS BOG‘LOVCHILARINING FIZIK-MEXANIK XOSSALARINI YAXSHILASH	**376**
86.	**Ashurova Sevara Ilxom qizi,** UMUMIY O‘RTA TA’LIM MAKTABLARIDA O‘QUVCHI-QIZLAR O‘RTASIDA VOLEYBOL SPORT TURINI OMMALASHTIRISHNING PEDAGOGIK SHART-SHAROITLARINI TAKOMILLASHTIRISH	**383**
87.	**Muradova Shodiya Zokir qizi,** CHO‘LPON HIKOYALARIDA AYOLLAR ERKI G‘OYALARI («NOVVOY QIZ» VA «QOR QO‘YNIDA LOLA» HIKOYALARI ASOSIDA)	**388**
88.	**Norboyeva Farangiz Alisher qizi,** BOSHLANG‘ICH SINF O‘QUVCHILARINING NUTQIY FAOLLIGINI RIVOJLANTIRISHDA NUTQNI TANISH TEXNOLOGIYALARIDAN FOYDALANISH METODIKASI	**391**
89.	**Orifjanov Shavkatbek Shuxratbek o’g’li,** TEXNOLOGIK JARAYONLARDA NOSOZLIKLARNI SUN’IY INTELLEKT ASOSIDA OLDINDAN PROGNOZLASH USULLARI	**397**
90.	**Khaydarova Ziyodaxon Azimjon qizi,** AN IMPLICIT UPWIND DIFFERENCE SCHEME FOR THE BOUNDARY CONTROL PROBLEM OF HYPERBOLIC SYSTEMS	**402**