Latvijas Lauksaimniecības universitāte
Informācijas Tehnoloģiju fakultāte
Vadības sistēmu katedra

Latvia University of Agriculture
Faculty of Information Technologies
Department of Control Systems

Vitālijs Komašilovs

HETEROGĒNAS ROBOTU KOLONIJAS SPECIFIKĀCIJAS OPTIMIZĀCIJAS UZDEVUMA RISINĀŠANAS PROCEDŪRA

PROCEDURE FOR RESOLVING SPECIFICATION OPTIMIZATION TASK OF HETEROGENEOUS ROBOT COLONY

Promocijas darba
KOPSAVILKUMS
doktora grāda ieguvei
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Promocijas darba zinātniskais vadītājs: Latvijas Lauksaimniecības universitātes asociētais profesors Dr.sc.ing. Egils Stalidzāns

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Oficiālie recenzenti:

1. Rīgas Tehniskās universitātes profesors Dr.hab.sc.ing. Jānis Grundspeņķis
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1. Komasilovs, V., Stalidzans, E. (2010) Simulation of Real-Time Robot Control Systems Using Player/Stage Software. In: *Industrial Simulation Conference 2010*. Budapest, Hungary: Eurosys-ETI, p. 39–41.
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IEVADS

Pēdējo desmit gadu laikā daudzrobotu sistēmu izpētes nozare ir kļuvusi par vienu no aktuāliem virzieniem robotikā un daudzi pētnieki ir pievērsušies tai. Pirmie pētījumi tika vērsti uz daudzrobotu sistēmu funkcionālo principu izstrādi un nodrošināja pamatu turpmākiem pētījumiem. Lielākā daļa pētījumu daudzrobotu sistēmu virzienā ir vērsti uz gatava risinājuma izstrādi konkrētam uzdevumam. Ir pieejamas daudzas vadības arhitektūras, sakaru stratēģijas un citi risinājumi kas tiek pielietoti daudzrobotu sistēmās. Pretstatā ir relatīvi maz formālo metožu un analītisko risinājumu, kuri atbalstītu lēmumu pieņemšanu robotu sistēmu projektēšanas stadijā.

Neskatoties uz lielāku sarežģītību daudzrobotu sistēmu projektēšanā un izstrādē, tām ir vairākas priekšrocības salīdzinājumā ar viena robota sistēmām. Daudzrobotu sistēmu priekšrocības ietver šādus aspektus un pielietojuma īpatnības:

- ✓ sistēmas drošums un bojājumpiecietība ir panākta ar elementu papildus redundanci;

- ✓ uzdevumu izpilde, kuri ir ārpus viena robotu spējām, piemēram lielu un smagu objektu pārvietošana, sarežģīto struktūru montāža;
- ✓ uzdevumu izpilde, kurus nav ekonomiski izdevīgi realizēt izmantojot vienu daudzfunkcionālu robotu;
- ✓ ātra uzdevumu izpilde daudzkārtīgā paralēlisma dēļ, kas ir raksturīgs daudzrobotu sistēmām.

Salīdzinoši maz ir izpētītas daudzrobotu sistēmas, kas sastāv no heterogēniem robotiem. Tajās vismaz viens sistēmas vienums atšķiras no pārējiem ar tā mehāniskās, uztveršanas vai skaitļošanas aparatūras, vai iekšējās vadības arhitektūras risinājumu. Heterogēnām daudzrobotu sistēmām potenciāli ir raksturīgs paaugstināts drošuma līmenis un tās ir spējīgas nodrošināt uzticamu un elastīgu uzdevuma risinājumu.

Daudzrobotu sistēmas lietotājam, kas ir implementēta noteikta uzdevuma izpildei, viens no svarīgākiem radītājiem ir sistēmas izmaksas. Robotu klašu skaits, kā arī klašu funkciju specifikācija un katras klases eksemplāru skaits sistēmā ir parametri, kurus ir iespējams mainīt optimizējot sistēmas izmaksas. Praksē minētie parametri parasti ir noteikti iepriekš un tādejādi optimizācijas potenciāls netiek novērtēts. Kā rezultātā daudzrobotu sistēmas kļūst nepievilcīgas lietotājam. Tām trūkst skaidra izmaksu pozīciju aprēķina un parametru modificēšanas ietekmes prognozes.

Promocijas darbs attiecās uz daudzrobotu sistēmu raksturīgo pazīmju formālu noteikšanu un ir veltīts daudzrobotu sistēmu dažādu parametru optimizācijai, kas ļauj atrast visefektīvāko sistēmas konfigurāciju, spējīgu izpildīt definēto uzdevumu.

Promocijas darba mērķis un uzdevumi

Promocijas darba mērķis ir uzlabot heterogēno daudzrobotu sistēmu specifikācijas izstrādi projektēšanas stadijā analizējot pilnu risinājumu telpu nevis pārskatot tikai daļu no iespējamiem risinājumiem.

Darba mērķa sasniegšanai ir izvirzīti vairāki uzdevumi:

1. analizēt specifikācijas izstrādes metodes, kas ir pielietojamas heterogēnām daudzrobotu sistēmām;
2. definēt specifikācijas optimizēšanas uzdevumu un tā risinājuma konceptu heterogēnām daudzrobotu sistēmām;
3. izstrādāt procedūru optimālās heterogēnās daudzrobotu sistēmas specifikācijas meklēšanai pilnā risinājumu telpā;
4. izstrādāt heterogēno daudzrobotu sistēmu uzdevuma uzdošanas tehniku un tā dekompozīcijas paņēmienu;
5. analizēt iespējamo risinājumu telpas izmēru specifikācijas optimizēšanas uzdevumam;
6. implementēt un praktiski pārbaudīt heiristiskās meklēšanas metodi daudzrobotu sistēmas specifikācijas pirmās kārtas novērtēšanai;

7. analizēt iespēju izmantot imitācijas tehnikas daudzrobotu sistēmas specifikācijas otrās kārtas novērtēšanai.

Pētījuma metodes

Darba ietvaros tika izstrādāta speciāla programmatūra risinājuma telpas analīzes daudzrobotu sistēmu specifikācijas optimizācijas uzdevumam. Tas ietver moduļus sistēmas uzdevuma, komponenšu un to īpašību uzdošanai, risinājumu kandidātu ģenerēšanai, nepilnīgo kombināciju filtrēšanai un kopējā iespējamo risinājumu skaita noteikšanai. Programmatūra ir izstrādāta izmantojot *Java* programmatūras izstrādes platformu.

Speciālās kombinatoriskās analīzes metodes tika izmantotas risinājuma telpas novērtēšanai. Daudzrobotu sistēmas specifikācijas kandidātu pirmās kārtas novērtēšana ir implementēta izmantojot ģenētisko algoritmu, kura kodols ir balstīts uz *JGAP* pakotnes. Praktiskie eksperimenti tika izpildīti uz atvēlētās skaitļošanas aparatūras (*IBM 3850*).

Uz imitācijas modeļiem balstītā daudzrobotu sistēmas specifikācijas novērtēšana ir realizēta izmantojot iekārtu interfeisu un robotu vadības tīkla serveri *Player* un robotu populācijas imitācijas pakotni *Stage*.

Pētījuma tēzes

- ✓ Nav piedāvātas formālas metodes heterogēno daudzrobotu sistēmu specifikācijas izstrādei.
- ✓ Komponenšu primitīvu līmeņa ieviešana ļauj formāli aprakstīt daudzrobotu sistēmas uzdevumu.
- ✓ Daudzrobotu sistēmu specifikācijas izstrādes uzdevuma risinājuma telpas izmērs pieaug nelineāri atkarībā no komponenšu skaita.
- ✓ Ir iespējams izstrādāt visu risinājumu telpu aptverošu heterogēno daudzrobotu sistēmu specifikācijas optimizēšanas procedūru.

Zinātniskais jauninājums un praktiskā vērtība

- ✓ Heterogēnas daudzrobotu sistēmas specifikācijas optimizēšanas uzdevuma risinājums tiek definēts izmantojot detalizētus primitīvus, kas ietver komponentes un aģentus.
- ✓ Visu risinājumu telpu aptverošā heterogēno daudzrobotu sistēmu specifikācijas optimizēšanas procedūra nosaka darbplūsmu no biznesa prasību specifikācijas līdz ieteicamai daudzrobotu sistēmas specifikācijai.
- ✓ Izstrādātas formulas daudzrobotu sistēmu specifikācijas risinājumu telpas izmēra noteikšanai.
- ✓ Uz ģenētiskā algoritma balstīta heiristiskā meklēšana ir adaptēta daudzrobotu sistēmas specifikācijas optimizēšanas uzdevumam pielāgojot ģenētiskā attēlojuma, atbilstības funkcijas un evolūcijas procesa realizāciju.

- ✓ Daudzrobotu sistēmas vadības karkasa realizācija ir balstīta uz signālu apstrādes imitācijas vidē.

Izstrādātā specifikācijas optimizēšanas procedūra nodrošina biznesa prasību formālu analīzi un piedāvā karkasu optimālās heterogēnās daudzrobotu sistēmas konfigurācijas meklēšanai. Optimālās specifikācijas mērķis ir piesaistīt piemērotus aģentus un palielināt to komponenšu izmantošanu industriālajiem uzdevumiem. Tas palielina produkcijas sistēmas efektivitāti, kas savukārt samazina sistēmas uzturēšanas izmaksas un palielina uzņēmēja peļņu.

Autors redz iespēju izmantot aparatūras līmenī realizēto robotizēto sistēmu specifikācijas optimizēšanas procedūras noskaņošanai.

Praktiskā zāles pļaušanas aģenta aparatūras realizācija ir uzsākta autora vadītā maģistra darba ietvaros. Tiek veikti lauku eksperimenti ar autonomā zāles pļāvēja darba prototipu, kas ir aprīkots ar stūrēšanas un GPS sistēmām.

Darba struktūra un apjoms

Promocijas darbs ir uzrakstīts angļu valodā, satur anotāciju, ievadu, 6 nodaļas, secinājumus, literatūras sarakstu un 4 pielikumus, tajā skaitā 8 tabulas, 39 attēlus, 17 formulas, kopā 194 lapaspuses. Darbā izmantoti 247 literatūras avoti.

1. DAUDZROBOTU SISTĒMAS SPECIFIKĀCIJAS IZSTRĀDES PROBLĒMAS NOSTĀDNE

Pēdējā gadu desmitā daudzrobotu sistēmu izpētes virziens ir kļuvis par vienu no aktuālākiem robotikas nozarē. Pirmie pētījumi bija veltīti daudzrobotu sistēmu darbības pamatprincipu izstrādei (Balch, Parker, 2002; Parker et al., 2005) un nodrošināja metodisko pamatu turpmākiem pētījumiem.

Pētījumi daudzrobotu sistēmu virzienā ir atpalikuši salīdzinājumā ar viena robota sistēmām. Galvenokārt tas ir saistīts ar aparatūras un programmatūras risinājumu trūkumiem, kuri bija raksturīgi iepriekšējiem gadiem. Pat viena robota uzturēšanai bija nepieciešami ievērojami līdzekļi un laiks. Ar laiku robotu sistēmas kļuva uzticamākas un pieejamākas, pievēršot pētnieku interesi sistēmām, kas demonstrēja vairāku mobilo autonomo robotu kooperatīvo uzvedību.

1990-to gadu vidū vairāku robotu vadības virziens sāka strauji attīstīties. Iedvesmoti ar sociālo insektu fenomenu, pētnieki fokusējās uz vairāku robotu kooperatīvās vadības algoritmiem (Beni, Wang, 1993; Kube, Zhang, 1993). Mobilo robotu grupas tika uzbūvētas ar mērķi izzināt tādus aspektus kā grupas arhitektūra, resursu konflikti, kooperācijas principi, apmācība un citus (Cao et al., 1997).

Neskatoties uz lielāku projektēšanas un izstrādes sarežģītību, daudzrobotu sistēmām ir raksturīgas vairākas priekšrocības. Autonomo robotu grupas ir spējīgas izpildīt uzdevumus, kuri var būt sarežģīti, nevēlami, vai pat neiespējami atsevišķiem robotiem. Var minēt šādus pielietojuma piemērus (Bekey, 2005):

- ✓ attālā zondēšana bīstamajās vidēs, kurās viena robota bojājums nedrīkst novest pie visa uzdevuma neveiksmes;
- ✓ uzdevumu izpilde, kuri ir ārpus viena robota spējām, piemēram, lielu un smagu objektu pārvietošana, sarežģīto struktūru montāža;
- ✓ ātrāka uzdevumu izpilde, kuru veicina daudzrobotu sistēmām raksturīgais paralēlisms;
- ✓ sarežģīto uzdevumu izpilde ir izdevīgāka izmantojot vienkāršu un specializēto iekārtu grupu, salīdzinot ar viena daudzfunkcionālā robota izmantošanu;
- ✓ izkliedētā zondēšana izmantojot lielas vienkāršo un lēto robotu grupas.

Vairums pētījumu daudzrobotu sistēmu virzienā ir vērsti uz praktiskā risinājuma izstrādi konkrētam uzdevumam. Ir pieejamas vairākas vadības arhitektūras, saziņas stratēģijas, resursu plānošanas pieejas un citi algoritmi lietošanai daudzrobotu sistēmās (Burgard et al., 2005; Nouyan et al., 2009; Rybski et al., 2007). Pretstatā ir relatīvi maz formālo modeļu un analītisko risinājumu, kas apraksta notieku problēmu (Gerkey, 2003). Līdz ar to netiek veikta daudzrobotu sistēmas ekonomiskā labuma un strukturālā projektējuma analīze.

Uzdevuma realizācija izmantojot heterogēno daudzrobotu sistēmu var samazināt tās izmantošanas izmaksas, palielinot atsevišķu komponenšu izmantošanas laiku. Šajā gadījumā iespējamo risinājumu telpa daudzkārtīgi paplašinās jaunas parametru dimensijas dēļ – robotu tipi – kas tiek izmantoti sistēmas specifikācijas izstrādē. Tāpēc bieži tikai daži intuitīvi risinājumi tiek analizēt un labākais no tiem tiek uzskatīts par optimālo. Autora mērķis ir atrast optimumu pilnā risinājumu telpā pielietojot specifikācijas formalizāciju, sasniedzamības analīzi un skaitļošanas jaudu. Izmantojot piedāvāto procedūru optimums tiek atrasts pilnā risinājumu telpā novēršot suboptimālo risinājumu izmantošanu. Optimizācijas procedūra ir sadalīta astoņos secīgos soļos.

2. DAUDZROBOTU SISTĒMAS SPECIFIKĀCIJAS OPTIMIZĀCIJAS PROCEDŪRA

Robotu sistēmas *specifikācija* ir parametru kopa kas unikāli un pilnīgi apraksta sistēmu. Dažādas specifikācijas tiek iegūtas mainot sistēmas parametrus. Sistēmas specifikāciju var izmantot vienotai formālajai analīzei, jo tā nosaka visus būtiskus sistēmas parametrus. Heterogēno daudzrobotu sistēmu kontekstā specifikācija nosaka robotu tipus (klases) un to eksemplāru skaitu sistēmā.

Promocijas darba ietvaros *optimizācijas uzdevums* ir vērsts uz labākās specifikācijas atrašanu daudzrobotu sistēmai, maksimizējot mērķa funkciju. Tas nozīmē optimālā risinājumu meklēšanu pilnā iespējamo risinājumu telpā.

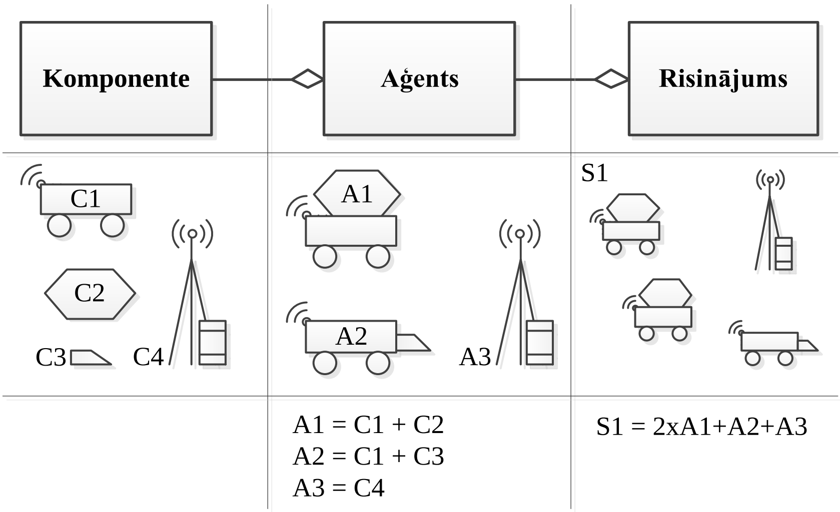
Heterogēnam daudzrobotu sistēmām iespējamo risinājumu kopa ietver visas robotu tipu un to eksemplāru skaita kombinācijas.

Optimizācijas process paredz *optimizācijas kritēriju*, *parametru* un *ierobežojumu* definēšanu. Autors izmanto *īpašuma kopējās izmaksas* kā universālu kritēriju specifikācijas optimizēšanas metodes demonstrācijai. Optimizācijas *parametrs* ir pati specifikācija. Optimizācijas ierobežojumus, galvenokārt, definē lietotājs atbilstoši paredzētām sistēmas izmantošanas īpatnībām.

Specifikācijas optimizēšanas konceptuālais (Komasilovs, Stalidzans, 2011) modelis ir balstīts uz dekompozīcijas pieejas. Notiek robotu sistēmas uzdevuma dekompozīcija komponenšu sarakstā, tādejādi definējot prasības formālajā veidā. *Komponentes* nosaka sistēmas funkciju abstraktas definīcijas nenorādot to realizācijas īpatnības.

Komponentes tiek grupētas *aģentos*, kuri atbilst sistēmas funkcionāliem vienībām. Disertācijas ietvaros par aģentiem tiek uzskatīti mobilie roboti (piemēram, transportētājs, iekrāvējs) vai stacionārās vienības (piemēram, komunikācijas vienība, noliktava).

Visbeidzot aģentu kopa tiek izvēlēta veidojot risinājumu. Pēc būtības, *risinājums* atbilst heterogēnās daudzrobotu sistēmas specifikācijai un tas nosaka aģentu tipus un to eksemplāru skaitu kas tiek izmantots uzdevuma izpildei. Konceptuālā modeļa grafiskais attēlojums ir parādīts 1. att.



1. att. **Risinājuma konceptuālais modelis**

Optimizācijas procedūra nosaka darbību secību kuras ir nepieciešamas optimālās (vai tuvas tai) vērtības atrašanai. Promocijas darba ietvaros tiek piedāvāta formāla pieeja heterogēno daudzrobotu sistēmu funkcionālo un strukturālo parametru (tās specifikācijas) analīzei, kā arī izmaksu optimizēšanai, ņemto vērā lietotāja definēto kritēriju un sistēmas izmantošanas īpatnības.

Izstrādātā procedūra piedāvā karkasu heterogēnās daudzrobotu sistēmas labākās specifikācijas meklēšanai. Procedūras mērķis ir atrast optimālo risinājumu pilnā risinājumu telpā un piedāvāt metodes neoptimālo risinājumu atzaru novēršanai agrīnās optimizācijas posmos.

Procedūras darbplūsma (sk. 2. att.) definē 8 secīgus soļus un var būt izpildīta iteratīvi (Komasilovs, Stalidzans, 2012).

1. solis. Pasūtītājs (lietotājs) definē daudzrobotu sistēmas biznesa prasības.

2. solis. Tiek veikta uzdevuma dekompozīcija komponentēs, tiek izvēlēti optimizācijas kritērijs, parametri un ierobežojumi.

3. solis. Risinājumu telpa tiek analizēta ar mērķi novērtēt iespējamo risinājumu skaitu.

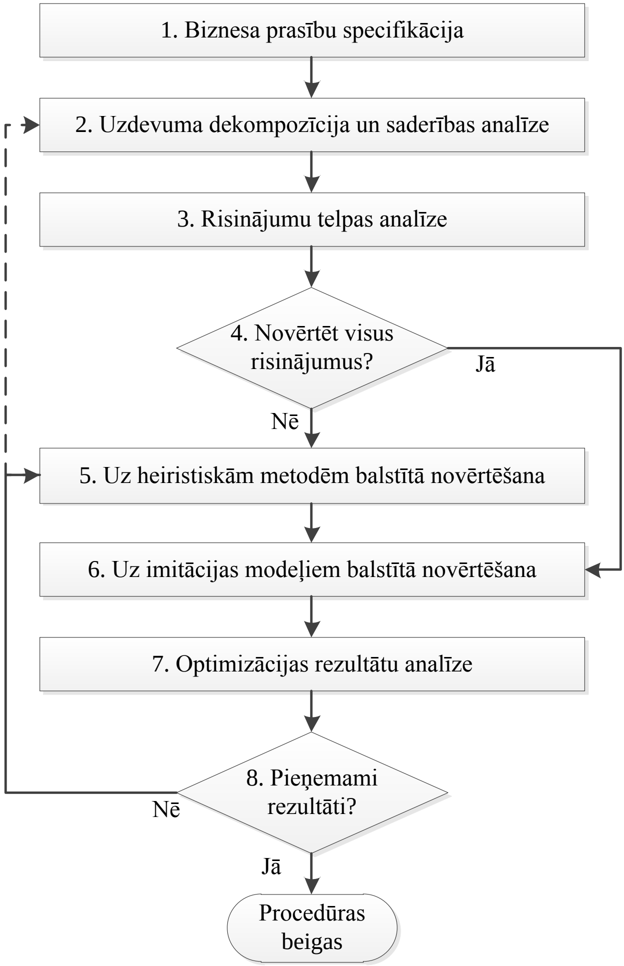
4. solis. Ja risinājumu skaits ir pārāk liels lai novērtēt tos visus, tad seko 5. solis, pretējā gadījumā 6. solis.

5. solis. Heiristiskie algoritmi tiek izmantoti pārmeklējamās risinājumu telpas samazināšanai un dažu piemērotāko risinājumu kandidātu izvēlei.

6. solis. Precīzā risinājumu kandidātu novērtēšana izmantojot imitācijas modeļus.

7. solis. Optimizācijas procesa rezultāti tiek analizēti ar mērķi izzināt atšķirības starp 5. un 6. soļos novērtēto piemērotību.

8. solis. Piemērotības modeļi tiek pieskaņoti ja atšķirības nav pieņemamas un procedūra tiek izpildīta atkārtoti.



2. att. **Specifikācijas optimizēšanas procedūra**

3. UZDEVUMA DEKOMPOZĪCIJA UN RISINĀJUMU TELPAS IZSTRĀDE

Pirmais procedūras solis nosaka biznesa prasību specifikāciju robotu sistēmai. Tiek definēts uzdevums, kas ietver apakšuzdevumus un sistēmas izmantošanas īpatnības. Šis solis atbilst biznesa prasību specifikācijas posmam sistēmas analīzes procesā.

Otrais procedūras solis ir paredzēts iepriekšējā solī iegūto sistēmas prasību formalizēšanai un sagatavošanai (dekompozīcijai) nākamajos soļos veicamajai optimizēšanai.

Specifikācijas optimizēšanas procedūra izmanto speciāli izstrādātu komponenšu klasifikācijas modeli kas atbalsta uzdevuma prasību dekompozīciju. Modelis ir iedvesmots no bioloģisko sugu klasifikācijas pieejas un tam ir kokveida struktūra, kas parasti ir kompaktāka salīdzinot ar sarakstiem. Tāpat, kokveida struktūra ir viegli paplašināma, pievienojot jaunus atzarus.

Piedāvātais komponenšu klasifikācijas modelis paredz, ka katrs tā elements ir taksons, kas apraksta noteiktu komponenti (funkcionalitāti). Komponenšu detalizācijas līmenis palielinās virzoties dziļāk kokveida struktūrā. Koka saknes elementi definē komponenšu kategorijas un loģiskās grupas, dziļākie koka elementi (atzari) atbilst noteiktiem robotu sistēmas komponentēm.

Komponentes ļauj norādīt tikai strukturālas uzdevuma īpašības. Tomēr uzdevuma dinamiskie raksturojumi paliek nenoteikti, un atsevišķu komponenšu izmantošanas īpašības uzdevuma kontekstā nav skaidras.

Papildus komponenšu jēdzienam tiek definēts apakšuzdevuma koncepts. Tas nosaka vienkāršus uzdevumus, kurus robotu sistēma var nepārprotami izpildīt. Tādejādi promocijas darba ietvaros uzdevums robotu sistēmai tiek uzdots izmantojot nepieciešamo komponenšu sarakstu un apakšuzdevumu kopu, kas nosaka sistēmas uzvedību.

Tiek veikta iteratīva *saderības ierobežojumu* analīze ar mērķi atmest sākotnēji neracionālos risinājumu kandidātus. Tas palīdz samazināt nākamajos procedūras soļos apstrādāto risinājumu kandidātu skaitu, kas kopumā paātrina tās izpildi.

4. IESPĒJAMO RISINĀJUMU TELPAS ANALĪZE

Trešais piedāvātās specifikācijas optimizēšanas procedūras solis atbilst risinājumu telpas analīzes, kas tiek piemērota iepriekšējā solī izstrādātai uzdevuma formālajai definīcijai. Šī soļa mērķis ir izzināt specifikācijas optimizēšanas problēmas sarežģītību un paredzēt iespējamo risinājumu skaitu. Analīzes rezultāti tiek izmantoti nākamajos soļos piemērotāko novērtēšanas paņēmienu izvēlei.

Pēc konceptuālā modeļa risinājums tiek veidots no aģentiem, kuri savukārt tiek veidoti no komponentēm. Unikālo aģentu skaits, kurus ir iespējams kombinēt no uzdotām komponentēm, atbilst visu iespējamo komponenšu kombināciju skaitam (1).

$$f(n) = \sum_{k=1}^{n} \frac{n!}{k!\,(n! - k!)} = 2^n - 1 \quad (1)$$

kur

n – uzdevumā definēto komponenšu skaits;
$f(n)$ – unikālo aģentu kopējais skaits.

Piemēroto risinājumu skaits atbilst iespējamo aģentu kombināciju skaitam un tiek aprēķināts līdzīgā veidā (2).

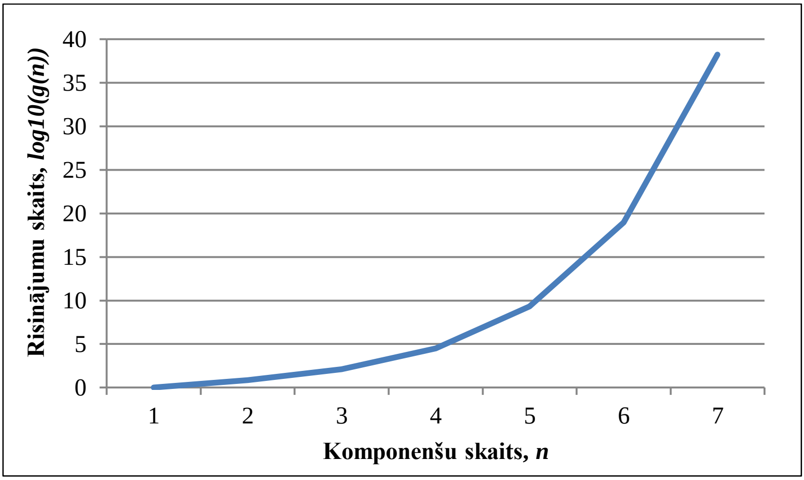
$$g(n) = \sum_{l=1}^{f(n)} \frac{f(n)!}{l!\,(f(n)! - l!)} - r(n) = 2^{2^n-1} - 1 - r(n) \quad (2)$$

kur

n – uzdevumā definēto komponenšu skaits;
$g(n)$ – risinājumu skaits;
$f(n)$ – unikālo aģentu skaits (1);
$r(n)$ – kombināciju skaits, kuras neatbilst risinājuma definīcijai.

Funkcija $r(n)$ norāda tādu kombināciju skaitu, kuras nevar uzskatīt par risinājumu trūkstošo komponenšu dēļ. Speciāla autora izstrādātā *CoMBot-Gen* programmatūra tika izmantota funkcijas vērtību eksperimentālai noteikšanai.

Tika noteikts gandrīz dubulti eksponenciāls risinājumu skaita pieaugums atkarībā no uzdoto komponenšu skaita (sk. 3. att.).

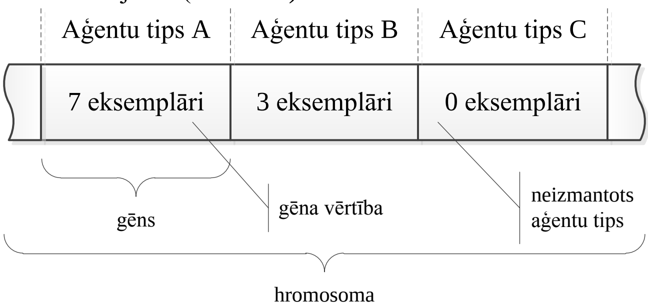


3. att. **Risinājumu skaita funkcija attēlota uz logaritmiskās skalas**

5. PIRMĀS KĀRTAS NOVĒRTĒŠANA IZMANTOJOT HEIRISTISKĀS METODES

Piektais procedūras solis ir paredzēts pirmās kārtas risinājumu kandidātu novērtēšanai izmantojot heiristiskās metodes. Pēc specifikācijas optimizēšanas procedūras šis solis nav obligāts un ir saprātīgi to izlaist, ja ir iespējama visu iespējamo risinājumu precīzā novērtēšanai. Promocijas darba ietvaros kā heiristiskās meklēšanas metodes piemērs tiek izmantots ģenētiskais algoritms (Eiben, Smith, 2003).

Risinājumu telpas ģenētiskais attēlojums nosaka tādu datu struktūru, kas ir piemērota datorizētai apstrādei un tajā pat laikā ir spējīga kodēt risinājuma kandidātu. Autors izmanto veselo skaitļu gēnus noteikta aģentu tipa eksemplāru skaita kodēšanai risinājumā (sk. 4. att.).



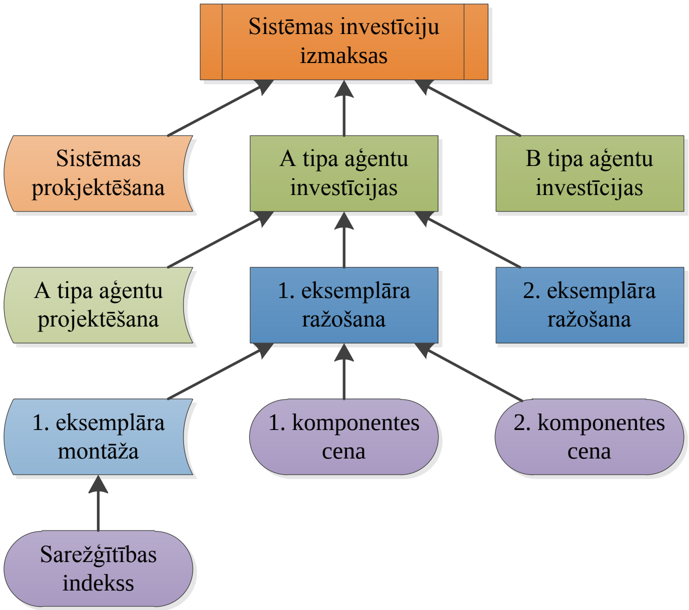
4. att. **Risinājumu telpas ģenētiskais attēlojums**

Ģenētiskā algoritma piemērotības funkcija atbilst skaitliskam radītājam, kas tiek piemērots katram risinājuma kandidātam populācijā. Piemērotības funkcija nosaka atsevišķa indivīda sniegumu attiecībā pret pašreizējo optimumu, tādejādi indivīdi tiek salīdzināti savā starpā. Autors izmanto īpašuma kopējās izmaksas kā pamata kritēriju risinājuma kandidātu novērtēšanai.

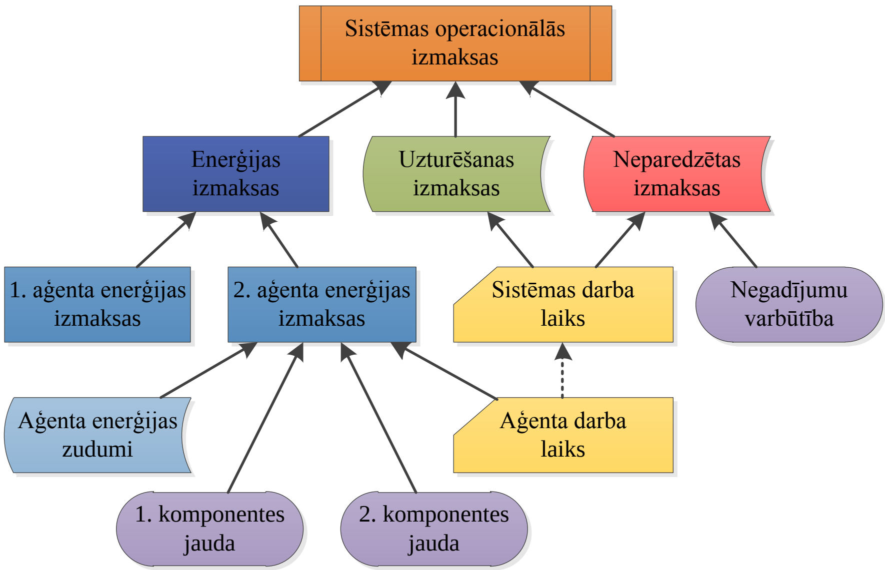
Tiek izdalītas divas īpašuma kopējo izmaksu pozīcijas (Komasilovs, 2012a): 1) investīciju izmaksas un 2) operacionālās izmaksas.

Investīciju izmaksu jēdziens attiecās uz izdevumiem, kas ir nepieciešami lai izveidot robotu sistēmu noteiktam uzdevumam. Tas definē izmaksu pozīcijas kuras rodas daudzrobotu sistēmas projektēšanas, izstrādes un izvēršanas laikā, bet neietver izmaksas kuras attiecās uz sistēmas darbību (sk. 5. att.).

Operacionālo izmaksu jēdziens attiecās uz izdevumiem kas rodas noteikta uzdevuma izpildes laikā. Daudzrobotu sistēmas operacionālās izmaksas ir lielā mērā atkarīgas no sistēmas pielietojuma īpatnībām. Saskaņā ar autora pieņēmumu operacionālās izmaksas ietver tādas pozīcijas, kā enerģijas, uzturēšanas un neparedzētās izmaksas (sk. 6. att).



5. att. **Investīciju izmaksu modeļa grafiskais attēlojums**

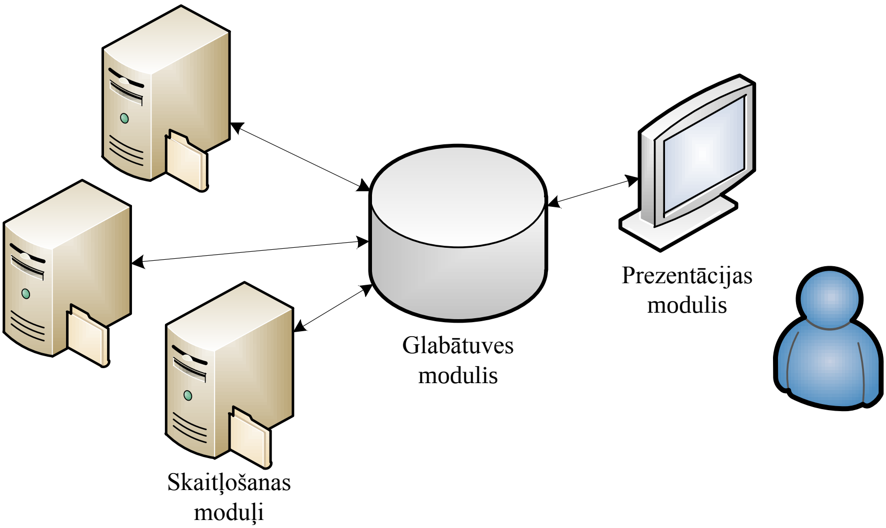


6. att. **Operacionālo izmaksu modeļa grafiskais attēlojums**

Speciāla autora izstrādātā *GAMBot-Eva* programmatūrā tika izmantota daudzrobotu sistēmu specifikācijas pirmās kārtas novērtēšanai. Programmatūra piedāvā funkcionalitāti, kas atbalsta optimizēšanas procedūras 5. soļa izpildi un realizē heiristisko meklēšanu plašā risinājumu telpā. Programmatūra balstās uz *JGAP – Java Genetic Algorithms and Genetic Programming Package* (Meffert et al., 2012) ģenētiskās skaitļošanas bibliotēkas. *MySQL* datubāze un tās klienta puses JDBC draiveri tiek izmantoti patstāvīgās datu glabātuves funkcionalitātes realizēšanai. Programmatūras pirmkods ir pieejams publiskā projekta vietnē (Komasilovs, 2012b).

Programmatūra atbalsta asinhrono vairāku ģenētiskā algoritma populāciju apstrādi uz izdalītā skaitļošanas servera. Sistēmas arhitektūra ietver šādus konceptus (sk. 7. att.):

- ✓ skaitļošanas modulis, kas izpilda ģenētisko algoritmu un vada tā populācijas evolūciju;
- ✓ prezentācijas modulis, kas nodrošina lietotāja saskarni skaitļošanas rezultātu izgūšanai;
- ✓ glabātuves modulis, kas nodrošina datu pastāvīgo glabāšanu un datu apmaiņu starp iepriekšējiem diviem moduļiem.



7. att. ***GAMBot-Eva* programmatūras arhitektūra**

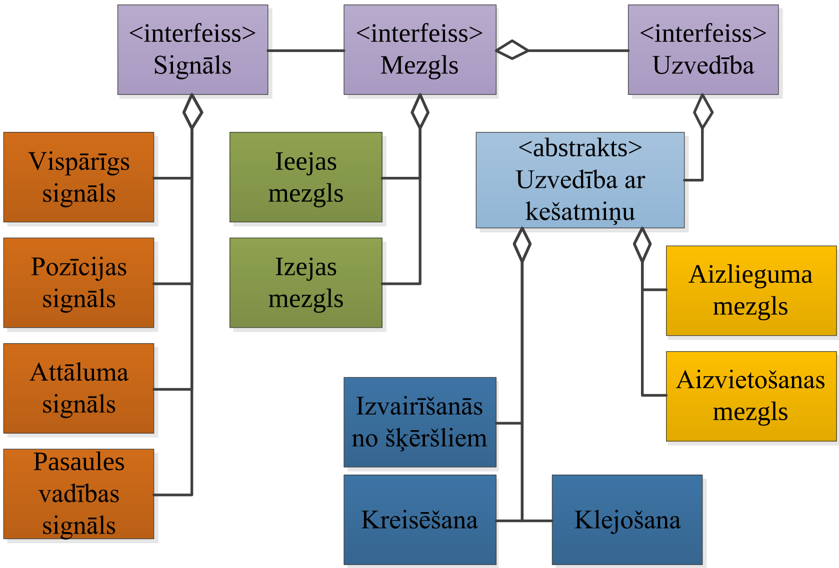
6. OTRĀS KĀRTAS NOVĒRTĒŠANA IZMANTOJOT IMITĀCIJAS MODEĻUS

Pēdējais specifikācijas optimizēšanas procedūras skaitļošanas posms (6. solis) atbilst daudzrobotu sistēmas specifikācijas kandidātu neliela skaita novērtēšanu izmantojot imitācijas modeļus. Galvenais šī soļa mērķis ir atdarināt vidi tuvu reālās dzīves situācijai un izmēģināt risinājuma kandidātus tajā. Imitācijas vide ir paredzēta reālās robotu sistēmas izstrādes aizvietošanai testēšanas stadijā.

Imitācijas vides konfigurācija paredz testējamās daudzrobotu sistēmas visu aģentu modeļu izstrādi, kā arī pašas vides (apkārtējās pasaules) modeļa izstrādi. Autors izmanto Player/Stage programmatūras kompleksu kā imitācijas pakotni, kas ir *The Player Project* ietveros izstrādātā atklātā pirmkoda programmatūra un tiek plaši pielietota daudzrobotu sistēmu un izkliedētās zondēšanas pētījumos (Gerkey et al., 2003).

Izvēlētai imitācijas programmatūrai ir elastīga un paplašināma arhitektūra, tā izmanto vienkāršus uz modeļu primitīviem balstītos konfigurācijas konceptus, un atbalsta zemā līmeņa pieeju pie imitētām iekārtām.

Imitēto aģentu vadības sistēmas izstrādes atbalstam autors ir izveidojis speciālo *SiMBot-Ctr* karkasu. Tas ir abstrakts rīks uz aizvietošanas arhitektūras balstīto vadības sistēmu izstrādei (sk. 8. att.). Karkass ļauj ātri un vienkārši būvēt vadības sistēmas izmantojot vispārinātas un abstraktas klases. Tāpat tas piedāvā vairāku biežāk lietoto robotu uzvedības scenāriju parametrizētu implementāciju. Vadības sistēma tiek būvēta no lietošanai gataviem blokiem, tādejādi atbalstot ātru prototipu izveidi.



8. att. ***SiMBot-Ctr* karkasa konceptuālais modelis**

Ņemot vērā paša imitācijas modeļa izstrādes izmaksas ir jāveic pieprasītās uz imitācijas modeļa balstītās novērtēšanas precizitātes analīzi. Vadības karkasā realizētā reaktīvā robotu vadības sistēmas arhitektūra demonstrē pieņemamu veiktspēju. Tomēr ir identificēta sistēmas līmeņa intelektuālas plānošanas nepieciešamība.

Detalizētā imitācijas modeļa izstrāde un imitēto aģentu intelektuālās vadības sistēmas implementēšana neietilpts disertācijas ietvaros veiktajos pētījumos.

Autors redz iespēju izmantot aparatūras līmenī implementēto robotu sistēmu specifikācijas optimizēšanas procedūras noskaņošanai. Zāles pļaušanas aģenta praktiskā aparatūras izstrāde ir uzsākta autora vadītajā maģistra darba ietvaros. Tiek veikti lauku eksperimenti ar autonomā zāles pļāvēja darba prototipu, kas ir aprīkots ar stūrēšanas un GPS sistēmām.

SECINĀJUMI

Galvenie darba rezultāti

Ir izstrādāta procedūra heterogēnās daudzrobotu sistēmas specifikācijas visu risinājumu telpu aptverošai optimizēšanai. Darba uzdevumi ir veiksmīgi izpildīti.

1. *Ir analizētas specifikācijas izstrādes metodes, kas ir pielietojamas heterogēnām daudzrobotu sistēmām.*

Aktuālākie daudzrobotu sistēmu izpētes virzieni tika apskatīti analīzes ietvaros. Autors secināja, ka lielākā daļā mūsdienu pētījumu ir vērsti uz konkrētā uzdevuma risinājuma izstrādi un pieskaņošanu. Tajā pat laikā ir relatīvi maz pētījumu, kuri ir vērsti uz formālo un universālo metožu izstrādi daudzrobotu sistēmām.

Autors konstatēja ka daudzrobotu sistēmu augstā līmeņa projektējums netiek nekādā veidā apstiprināts, bet pretstatā tiek balstīts uz pētījuma laikā pieejamām iekārtām. Tādejādi autors izvirzīja specifikācijas izstādes problēmu kā neatrisinātu aspektu daudzrobotu sistēmu kontekstā.

2. *Ir definēts heterogēnās daudzrobotu sistēmas specifikācijas optimizācijas uzdevums un risinājuma koncepts.*

Definīcijas ietver sevī optimizācijas uzdevuma kritēriju, ierobežojumus un parametrus. Autors izmanto kopējās īpašuma izmaksas kā integrālu optimizācijas kritēriju praktiskiem eksperimentiem, ņemot vērā robotu sistēmas izmantošanas īpatnības.

Iepriekš minētā optimizācijas uzdevuma risinājuma koncepts ir balstīts uz trim būtiskiem jēdzieniem: risinājums, aģents un komponente. Risinājums tiek definēts aģentu kopas veidā. Aģents atbilst sistēmas vienībai, mobilajam robotam vai stacionārai iekārtai. Aģenti tiek būvēti no komponentēm – sistēmas nedalāmiem primitīviem, kuri definē noteiktu funkcionalitāti bez tās implementācijas detaļām.

3. *Ir izstrādāta procedūra optimālās heterogēnās daudzrobotu sistēmas specifikācijas meklēšanai pilnā risinājumu telpā.*

Procedūrai ir iteratīvs raksturs un tā sastāv no astoņiem secīgiem soļiem. Vispirms tiek definētas biznesa prasības, tad notiek to dekompozīcija risinājuma konceptos. Pēc tam tiek veikta risinājuma telpas analīze un tiek pielietoti dažādas risinājumu kandidātu novērtēšanas metodes. Visbeidzot, optimizācijas rezultāti tiek analizēti, un, ja tas ir nepieciešams, uzdevuma nostādne tiek precizēta un tiek uzsākta jauna procedūras iterācija.

4. *Ir izstrādāta heterogēno daudzrobotu sistēmu uzdevuma uzdošanas tehnika un tā dekompozīcijas paņēmiens.*

Pēc specifikācijas optimizēšanas procedūras koncepta daudzrobotu sistēmas uzdevums tiek definēts izmantojot komponentes, kuras ir nepieciešamas uzdevuma izpildei. Ir definēti komponenšu klasifikācijas un īpašību uzdošanas principi.

5. *Ir analizēts iespējamo risinājumu telpas izmērs specifikācijas optimizēšanas uzdevumam.*

Tika izstrādātas speciālas metodes unikālo aģentu tipu un to iespējamo kombināciju skaita noteikšanai. Izstrādātā *CoMBot-Gen* programmatūra ļauj veikt aģentu kombināciju analīzi un atmest nederīgās kombinācijas. Ir noteikts gandrīz dubulti eksponenciāls risinājumu skaita pieaugums atkarībā no uzdoto komponenšu skaita.

6. *Heiristiskās meklēšanas metode tika implementēta un eksperimentāli pārbaudīta daudzrobotu sistēmu specifikācijas pirmās kārtas novērtēšanai.*

Ir izstrādāta modulāra *GAMBot-Eva* programmatūra uz ģenētiskā algoritma balstītai heiristiskai meklēšanai. Programmatūra tiek izmantota kā universāls rīks risinājumu kandidātu pirmās kārtas novērtēšanai. Ģenētiskā algoritma implementācija ietver ģenētiskā attēlojuma un piemērotības funkcijas izstrādi, kas novērtē sistēmas īpašuma kopējās izmaksas. Ir veiksmīgi veikti praktiskie eksperimenti risinājumu kandidātu pirmās kārtas novērtēšanas etapa dažādu aspektu testēšanai.

7. *Ir analizēta iespēja izmantot imitācijas tehnikas daudzrobotu sistēmas specifikācijas otrās kārtas novērtēšanai.*

Praktiskie eksperimenti ar izstrādāto *SiMBot-Ctr* vadības sistēmas karkasu apstiprina iespēju izmantot imitācijas tehnikas precīzai risinājumu kandidātu novērtēšanai. Tomēr ir svarīgi novērtēt nepieciešamo imitācijas modeļa detalizācijas pakāpi, jo paša modeļa izstrāde un imitācijas eksperimenti ir sarežģīti un laika ietilpīgi.

Secinājumi un attīstības perspektīvas

Daudzrobotu sistēmu formālā analīze un dažādu funkciju izmantošanas prognozēšana netika izpētīta daudzrobotu sistēmu pētījumu virzienā. Pareizi projektētā daudzrobotu sistēma pieprasa mazākas investīcijas no tās pasūtītāja un tajā pat laikā ir spējīga nodrošināt veiktspēju un drošumu, kas ir nepieciešams veiksmīgai uzdevuma izpildei.

Ir piedāvāta procedūra daudzrobotu sistēmas specifikācijas optimizēšanai. Tā nosaka darbplūsmu optimizēšanas uzdevuma atrisināšanai un ietver sevī tādus posmus kā biznesa prasību specifikācija, uzdevuma dekompozīcija komponentēs, risinājuma telpas analīze, risinājuma kandidātu novērtēšanu izmantojot heiristiskos algoritmus un imitācijas modeļus.

Analītiskā iespējamo aģentu kombināciju skaita novērtēšana specifikācijas optimizēšanas problēmai atklāj gandrīz dubulti eksponenciālu atkarību no uzdoto komponenšu skaita.

Autors saredz vairākas nākotnes attīstības perspektīvas, kuras uzlabotu piedāvāto specifikācijas optimizēšanas procedūru:

- ✓ uzlabot komponenšu un to īpašību uzdošanas modeli, kas ļautu elastīgāku to investīcijas un operacionālo izmaksu uzdošanu;
- ✓ izstrādāt īpašuma kopējo izmaksu novērtēšanas modeli, kas būtu balstīts uz modernām ekonomiskās plānošanas metodēm;
- ✓ palielināt izstrādātās programmatūras parametrizēšanas pakāpi, kas paplašinātu tās izmantošanas iespējas;
- ✓ izstrādāt universālu konceptu robotu sistēmas globālā uzdevuma apakšuzdevumu definēšanai, kas padarītu optimizēšanas procedūras implementāciju universālāku;
- ✓ papildināt optimizēšanas procedūru ar soli, kas būtu balstīts uz ātrā un tuvinātā imitācijas modeļa;
- ✓ paplašināt imitēto daudzrobotu sistēmu vadības karkasa funkcionalitāti ar operacionālās plānošanas moduļiem;
- ✓ padarīt optimizācijas procesu un tā programmatūras implementāciju interaktīvu un nepārtrauktu, kā arī dot lielāku pārvaldību pār optimizācijas procesa un tā rezultāta īpatnībām;
- ✓ analizēt iespēju izmantot piedāvāto specifikācijas optimizēšanas procedūru citās nozarēs izplatot tās pieeju, kā arī, otrādi, iegūt zināšanas un metodes no citām nozarēm.

PARTICULARS

Research was executed at: Latvia University of Agriculture, Faculty of Information Technologies, Department of Computer Systems, Liela st. 2, Jelgava, Latvia

Experimental research was executed at: Latvia University of Agriculture, Faculty of Information Technologies, Computer Systems Department, Liela st. 2, Jelgava, Latvia

Scientific Advisor of the Doctoral Thesis: Dr.sc.ing. Egils Stalidzans, Associate Professor, Latvia University of Agriculture

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The defense of the doctoral thesis will take place at the open session of the Promotion Council in the field of Information Technologies of LUA at 13:30 on 09 May 2013, Room No. 218, Faculty of Information Technologies. Liela st. 2, Jelgava.

You are welcome to send your comments, signed and in a scanned form to secretary of Promotion Council – Liela st. 2, Jelgava, LV-3001;
phone (+372) 63 00 56 21; e-mail: tatjana.tabunova@llu.lv.

Council Secretary: lecturer, Mg.paed. Tatjana Tabunova.

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APPROBATION OF PHD THESIS

The research results of PhD thesis are presented in the following publications:

1. Komasilovs, V., Stalidzans, E. (2010) Simulation of Real-Time Robot Control Systems Using Player/Stage Software. In: *Industrial Simulation Conference 2010*. Budapest, Hungary: Eurosys-ETI, p. 39–41.
2. Komasilovs, V., Stalidzans, E. (2011) Functional decomposition method reveals the number of possible specifications of multi-robot system. In: *2011 IEEE 12th International Symposium on Computational Intelligence and Informatics (CINTI)*. Budapest, Hungary: IEEE, p. 161–165.
3. Komasilovs, V. (2012a) Investment and running cost estimation for heterogeneous multi-robot system. In: *5th International Scientific Conference on Applied Information and Communication Technology*. Jelgava, Latvia, p. 118–122.
4. Komasilovs, V. (2012b) Investment costs optimization of multi-robot system using genetic algorithm. In: *Annual 18th International Scientific Conference "Research for Rural Development 2012"*. Jelgava, Latvia, p. 229–232.
5. Komasilovs, V., Stalidzans, E. (2012a) Genetic algorithm used for initial evaluation of specification of multi-robot system. In: *13th International Carpathian Control Conference*. High Tatras, Slovakia: IEEE, p. 313–317.
6. Komasilovs, V., Stalidzans, E. (2012b) Procedure of Specification Optimization of Heterogeneous Robotic System. In: *IEEE 10th Jubilee International Symposium on Applied Machine Intelligence and Informatics (SAMI)*. Herl'any, Slovakia: IEEE, p. 259–263.
7. Komasilovs, V. (2013) Software modules for optimization of specification of heterogeneous multi-robot system. In: *12th International Scientific Conference Engineering for Rural Development*. Jelgava, Latvia, p. <in–press>.

The research results were presented at the following conferences:

1. Komasilovs, V., Stalidzans, E. Simulation of Real-Time Robot Control Systems Using Player/Stage Software. *Industrial Simulation Conference.* Budapest, Hungary. June 7-9, 2010.
2. Komasilovs, V. Concept of Functional Decomposition Method Used for Optimization of Specification of Heterogeneous Multi-robot System. In *RTU 52nd International Scientific Conference*. Riga, Latvia. October 13-15, 2011.

3. Komasilovs, V. Complexity analysis of decomposition approach used for optimization of specification of multi-robot system. In *Joint 3rd World Congress of Latvian Scientists and 4th Letonica Congress "Science, Society and National Identity"*. Rīga, Latvija. October 24-27, 2011.
4. Komasilovs, V., Stalidzans, E. Functional decomposition method reveals the number of possible specifications of multi-robot system. In *2011 IEEE 12th International Symposium on Computational Intelligence and Informatics (CINTI)*. Budapest, Hungary. November 21-22, 2011.
5. Komasilovs, V., Stalidzans, E. Procedure of Specification Optimization of Heterogeneous Robotic System. In *IEEE 10th Jubilee International Symposium on Applied Machine Intelligence and Informatics (SAMI)*. Herl'any, Slovakia. January 26-28, 2012.
6. Komasilovs, V. Investment and running cost estimation for heterogeneous multi-robot system. In *5th International Scientific Conference on Applied Information and Communication Technology*. Jelgava, Latvia. April 26-27, 2012.
7. Komasilovs, V. Investment costs optimization of multi-robot system using genetic algorithm. In *Annual 18th International Scientific Conference "Research for Rural Development 2012"*. Jelgava, Latvia. May 16-18, 2012.
8. Komasilovs, V., Stalidzans, E. Genetic algorithm used for initial evaluation of specification of multi-robot system. In *13th International Carpathian Control Conference*. High Tatras, Slovakia. May 28-31, 2012.
9. Komasilovs, V. Specification optimization of heterogeneous multi-robot systems. In open seminar of *"Development of intellectual multi-agent robotic system"*. Riga, Latvia. January 11, 2013.

INTRODUCTION

During the last decade multi-robot systems research field has become one of the most actual directions in the robotics and many researchers have focused on it. Early researches laid the foundation of the multi-robot system functional principles and therefore provided a solid base for the following investigations. Most of the researches in multi-robot systems field have a trend to focus on the development of working solution for a particular task. For now there are available a lot of different control architectures, communication strategies and other approaches developed to be used in multi-robot system. From the other side there are relatively few formal models and analytical solutions that support decision making during design stage.

Despite increased complexity in design and development of multi-robot systems, it has various advantages over single-robot systems. The list of advantages of multi-robot systems includes aspects and applications as follows:

- ✓ robustness or fault tolerance of the system which is achieved by additional redundancy;
- ✓ tasks which are beyond the limits of single robot like moving the large and heavy objects, assembly of complex structures;
- ✓ tasks which are too complex to be cost effective to perform by single multi-purpose robot;
- ✓ rapid task execution due to massive parallelism in multi-robot system.

Relatively less explored are the multi-robot systems that are composed from heterogeneous robots, which means that at least one member of such system differs from others by mechanical, sensing or processing hardware, or by internal control architecture. Heterogeneous multi-robot systems potentially have larger fault tolerance degree and are capable for redundant solutions of a problem, as well as more versatility in performing complex tasks.

For a user of multi-robot system implemented to perform certain task one of the major indicators are the costs of the system. The number of robot classes, as well as the specification of functions of each class and the number of instances of each class in the system are the parameters of the system that could be adjusted in order to optimize the costs of the system. In practice mentioned parameters are usually predefined and optimization potential is not assessed. As a result multi-robot system becomes unattractive for the customer because of lack of clear calculations in all positions of costs and predictable results of adjusting the parameters of system.

The thesis refers to the formal identification and quantification of the characteristics of multi-robot systems and it is devoted to the approach of optimization of various parameters of multi-robot systems to reach the most efficient set-up of system for a particular task assigning necessary functionality to instances of robot classes.

Goal and objectives of the thesis

The goal of the thesis is to improve the specification development for heterogeneous multi-robot systems during design stage by analyzing the full solution domain instead of testing only a part of possible solutions.

In order to achieve the goal of the thesis the list of objectives were defined as follows:

1. perform analysis of specification development methods applied for heterogeneous multi-robot systems;
2. define specification optimization task and its solution concept for heterogeneous multi-robot systems;
3. develop the procedure for finding optimal specification of heterogeneous multi-robot system in full solution domain;
4. develop mission definition technique and its decomposition approach for heterogeneous multi-robot systems;

5. perform the analysis of the size of feasible solution domain of the specification optimization task;
6. implement and experimentally test heuristic search algorithm for initial evaluation of specifications of multi-robot system;
7. analyze possibility to use simulation techniques for fine evaluation of specification of multi-robot system.

Research methods

Custom software is developed for analysis of solution domain of specification optimization task for multi-robot systems. This includes modules for defining the missions, components and their properties, for generating solution candidates, for filtering incomplete combinations and for estimating the total number of possible solutions. The software is developed using Java programming language.

Custom methods of combinatorial analysis are applied to assess the solution domain of the problem. Initial evaluation of specification candidates of multi-robot system is implemented using genetic algorithm, the kernel for genetic processing is provided by JGAP framework. Practical experiments are executed on dedicated processing hardware available in university (IBM 3850).

Simulation based evaluation of specification of multi-robot system is implemented using Player device interface and network server for robot control (a hardware abstraction layer for robotic devices) and Stage simulation package for population of mobile robots.

Theses

- ✓ There is a lack of formal methods for the development of optimal specification of heterogeneous multi-robot systems.
- ✓ Introduced level of the component primitives allows formal mission definition for the multi-robot systems.
- ✓ The size of the solution domain of the specification development problem for heterogeneous multi-robot systems depending on the number of components grows nonlinearly.
- ✓ It is possible to develop full solution domain scale specification optimization procedure for heterogeneous multi-robot systems.

Scientific novelty and practical value

- ✓ Specification optimization task for a heterogeneous multi-robot system is defined using detailed concepts for the solution including component and agent primitives.
- ✓ Full solution domain covering heterogeneous multi-robot system specification optimization procedure is developed defining the workflow

from the business requirements specification to the preferred specification of the multi-robot system.

- ✓ Formulas for determination of the number of solutions in the specification domain of multi-robot system are developed.
- ✓ Genetic algorithm based heuristic search is adapted for the specification optimization task adapting techniques for implementation of the genetic representation, the fitness function and the evolution processing.
- ✓ Signal based processing is implemented within the framework for control of multi-robot system in the simulated environment.

The developed specification optimization procedure enables formal analysis of the business requirements and provides a framework for finding the optimal setup of the heterogeneous multi-robot system. Optimal specification aims to apply appropriate agents and the increase utilization of their components in industrial applications. That leads to the increased efficiency of the production system, which in turn lowers the maintenance costs of the system and increases industrialist's income.

The author sees the possibility to use the robotic system implemented using a real hardware for fine tuning of the specification optimization procedure.

Practical hardware implementation of grass mowing agents is started within the master's thesis supervised by the author. Field experiments with the he working prototype of autonomous grass mower with steering and GPS system are running.

PhD thesis structure and volume

The PhD thesis is written in English containing abstract, introduction, 6 chapters, conclusions, bibliography and 4 annexes, including 8 tables, 39 pictures, 17 formulas, 194 pages in total. 247 literature sources were used.

1. DEFINING THE PROBLEM OF SPECIFICATION SELECTION FOR MULTI-ROBOT SYSTEM

During the last decade multi-robot systems research field become one of the most actual directions in the robotics and many researchers have focused on it. Early researches laid the foundation of the multi-robot system functional principles (Balch, Parker, 2002; Parker et al., 2005) and therefore provided a solid base for the following investigations.

Research on multiple mobile robots has lagged behind research on single robots. Major reason for it is that for many years robot hardware and software was very unreliable and required huge amount of effort to keep single robot working. Over time, robotic systems have become more available and much cheaper. There has been increased research interest in systems composed of multiple autonomous mobile robots exhibiting cooperative behavior.

In the mid-1990s multiple robot control direction began to change quickly. Researchers inspired by the phenomena of social insects focused on development of various algorithms for cooperative control of multiple robots (Beni, Wang, 1993; Kube, Zhang, 1993). Groups of mobile robots were constructed, with an aim to study such issues as group architecture, resource conflict, origin of cooperation, learning, and geometric problems (Cao et al., 1997).

Despite increased complexity in design and development of multi-robot systems, they have various advantages over single-robot systems. Groups of autonomous robots are able to perform tasks that may be difficult, undesirable, or impossible for single robot. Some of them are as follows (Bekey, 2005):

- ✓ explorations in hazardous environments where failure of one robot should not lead to failure of the entire mission and where redundancy may increase the fault tolerance of the colony;
- ✓ tasks beyond the limits of single robots, like cooperative lifting or pushing large and heavy objects or assembly of complex structures;
- ✓ tasks that can be completed more rapidly by multiple robots than possible is for a single robot due to massive parallelism in multi-robot system;
- ✓ complex tasks that may be less expensive with a group of specialized, simpler vehicles that with single, multipurpose robot;
- ✓ highly distributed sensing, in which large colonies of simple and inexpensive robots are used as mobile, communicating sensors.

Most of the researches in multi-robot systems field had a trend to focus on the development of working solution for a particular task. For now there are available control architectures, communication strategies or approaches developed to use in multi-robot system (Burgard et al., 2005; Nouyan et al., 2009; Rybski et al., 2007). From the other side there are relatively few formal models and analytical solutions that describe specific type of problem (Gerkey, 2003). Because of aforementioned assumptions the analysis of economic benefit and/or structural design of a multi-robot system are not performed.

Mission implementation using heterogeneous robot group can reduce costs by increasing utilization of particular components of robotic system. In this case the space of possible solutions expand dramatically due to new dimension of parameters – types of robots – added to the scope of choice of robot specification and their number in a homogenous group. Therefore often just several intuitive solutions are analyzed and the best of them is considered as optimal. The author aims to search the optimum in the full space of solutions applying formalization of the specification, feasibility analysis and computational power. Through proposed procedure optimum is found in full solution domain eliminating application of suboptimal solutions. The optimization procedure is divided in eight consecutive steps.

2. PROCEDURE FOR OPTIMIZATION OF SPECIFICATION OF MULTI-ROBOT SYSTEM

A *specification* of robotic system is a set of parameters that uniquely specify the system. Different specifications are obtained varying parameters of the system. Since a specification is a set of all relevant parameters of the system, it could be used to formally analyze the system as a single entity.

In the scope of heterogeneous multi-robot systems the specification defines types of robots (classes) as well as a number of instances of each class of robots in the system.

Within the scope of the thesis the *optimization task* is aimed to find best specification of a multi-robot system maximizing an objective function. This means the searching for an optimal solution in a full space of possible solutions. For a heterogeneous multi-robot system possible solutions include all combinations of robot types and number of their instances.

An optimization process implies that *optimization criterion*, *parameters* and *constraints* are defined. The author uses the *total costs of ownership* as a universal criterion for demonstrating specification optimization method. *Parameter* of the optimization is specification itself. Optimization *constraints* are primarily defined by user according to expected application peculiarities of the system.

The conceptual model (Komasilovs, Stalidzans, 2011) of specification optimization is based on decomposition approach. The mission for the robotic system is decomposed into the list of components, thereby defining the requirements in the formal manner. *Component* stands for an abstract definition of ability (function) of the system without an explicit specification of its realization.

Next, components are grouped together in order to form agents. In general, an *agent* is a functional unit of the system. Within the thesis agents are considered to be mobile robots (e.g. transporter, observer) or stationary units (e.g. communication unit, warehouse).

Finally a set of agents is selected to form a solution. *Solution* is a specification of heterogeneous multi-robot system, it defines types of agents (classes) and a number of their instances used to carry out a mission. Graphical representation of the conceptual model is shown on figure 1.

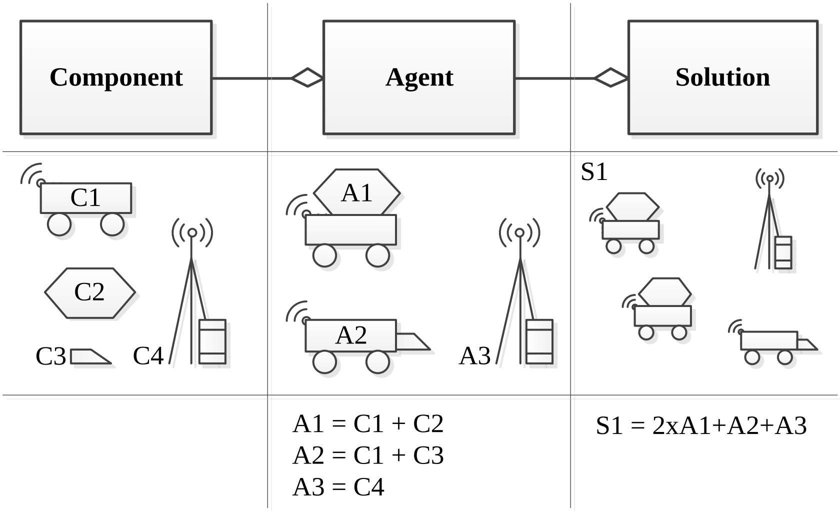

Figure 1. **Conceptual model of solution**

Optimization procedure stands for the sequence of actions which are needed to find the optima or close to that value. A formal approach is proposed within the thesis, which is used for analysis of the functional and structural parameters of heterogeneous multi-robot system (its specification), as well as for the optimization of its costs taking into account customer's criteria and peculiarities of the multi-robot system.

The developed procedure provides a framework for finding best specification of the heterogeneous multi-robot system. It aims to optimal solution searching in full solution domain and provides methods to eliminate non-optimal solution domain branches on early stages of optimization.

Figure 2 shows basic flowchart of the specification optimization procedure (Komasilovs, Stalidzans, 2012). It consists of 8 consecutive steps and can be executed iteratively.

Step 1. The business requirements for multi-robot system are defined by customer (user).

Step 2. Mission definition is decomposed into components, optimization criteria, adjustable parameters and constraints are selected.

Step 3. Solution domain is analyzed in order to assess the total number of possible solutions.

Step 4. If the number of solutions is too high to evaluate all of them, then proceed to the step 5. Otherwise one should go towards step 6.

Step 5. Heuristic algorithms are used to narrow the scope of considerable options to the bunch of fittest solution candidates.

Step 6. Fine evaluation is performed using simulations in order to select optimal solution for particular mission.

Step 7. The results of the optimization process are analyzed to find out the differences between forecasted fitness in step 5 and step 6.

Step 8. If the differences are not acceptable then parameters of initial evaluation is tuned to meet the requirements (step 5) or the different decomposition of the mission is applied and the procedure is executed again.

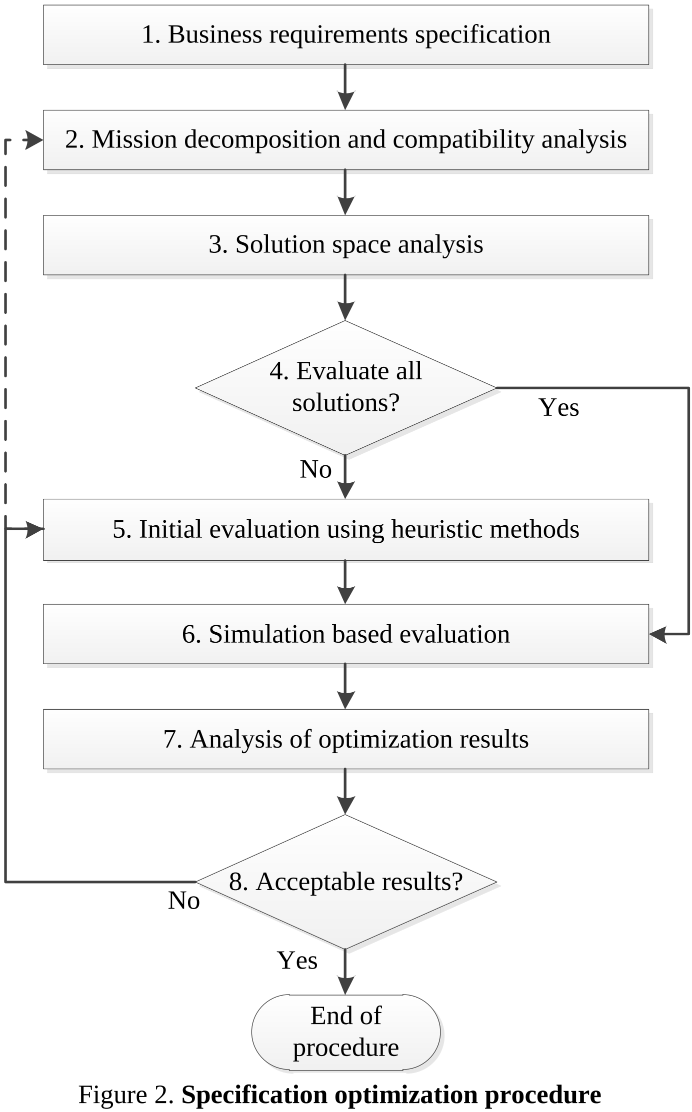

Figure 2. **Specification optimization procedure**

3. MISSION DECOMPOSITION AND SOLUTION DOMAIN DEVELOPMENT

The first step of the procedure stands for specification of business requirements for the robotic system. The mission is defined, which includes tasks and usage peculiarities of the system. This step corresponds to business requirements specification stage of the system analysis process.

The second step of the specification optimization procedure is aimed to formalization of system requirements obtained from previous step and preparing them (decomposing the mission) for consecutive optimization performed in next steps.

The specification optimization procedure uses custom component classification approach for supporting decomposition of the mission requirements. It is inspired by biological classification of species and follows tree structure. Trees are usually more compact in comparison to the lists. Also, tree structure is easily extendable by adding new branches.

Proposed component classification implies that each element of classification tree is a taxon, which describes certain component (functionality). The level of details of particular component increases going deeper through the tree. Root elements of the tree define categories and logical groups of components, deeper elements of tree (branches) are the specific components of robot system.

Components allow specifying only structural features of the mission. However dynamic features of the mission remain undefined and the application of certain component within the context for the mission is unclear.

In addition to the list of components, the concept of the tasks is defined. They stand for simple independent missions, which can be univocally performed by robotic system. Thereby the mission for the robotic systems considered within the thesis is defined using the list of components as well as the list of tasks, which define behavior of the system.

The iterative analysis of *compatibility constraints* is performed to eliminate initially irrational solution candidates. This allows decreasing the number of processed solution candidates during the next steps of the procedure, which leads to faster processing in general.

4. ANALYSIS OF DOMAIN OF FEASIBLE SOLUTIONS

The third step of proposed specification optimization procedure stands for solution domain analysis, which is applied on formal definition of the mission developed within previous step of the procedure. The main goal of this step is to recognize the complexity of the specification optimization problem and predict the number of feasible solutions. The results of the analysis are used for selecting appropriate optimization and evaluation approach for subsequent steps of the proposed procedure.

According to conceptual model of the solution is formed from agents, which in turn are composed from components. The number of agents which are possible to combine from defined components is equal to the number of all possible combination of the components (1).

$$f(n) = \sum_{k=1}^{n} \frac{n!}{k!\,(n! - k!)} = 2^n - 1 \qquad (1)$$

where

n – number of defined components for the mission;

$f(n)$ – total number of unique agents.

The number of valid solutions corresponds to the combinations of the agents and is obtained using similar approach (2).

$$g(n) = \sum_{l=1}^{f(n)} \frac{f(n)!}{l!\,(f(n)! - l!)} - r(n) = 2^{2^n - 1} - 1 - r(n) \qquad (2)$$

where

n – number of defined components for the mission;

$g(n)$ – number of solutions;

$f(n)$ – number of unique agents (1);

$r(n)$ – number of combinations, which are not solutions.

The function $r(n)$ represents the number of combinations, which cannot be considered as solutions because of missing components. Special software *CoMBot-Gen* was developed by the author in order to experimentally obtain its value.

Near double exponential growth of number of solutions as a function of the number of defined component is found (see figure 3).

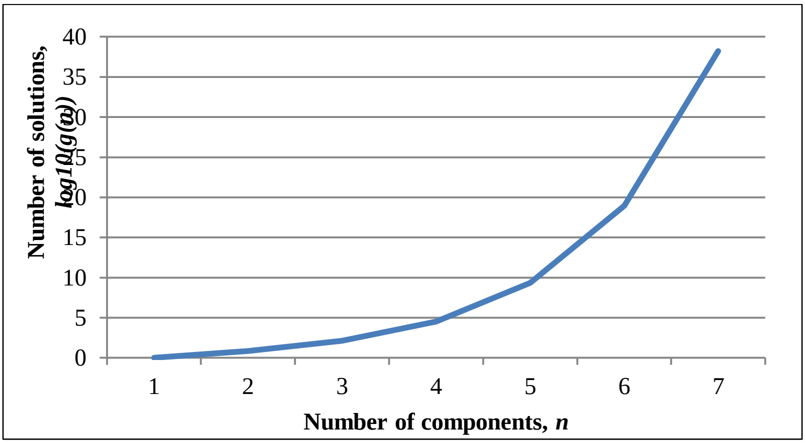

Figure 3. **Number of solutions plotted on logarithmical axis**

5. INITIAL EVALUATION USING HEURISTIC METHODS

The fifths step of proposed specification optimization procedure stands for initial evaluation of solution candidates using heuristic methods. According to the procedure this step is optional and it is reasonable to skip it if an analysis of all the number of solution candidates is feasible. A genetic algorithm is utilized within the thesis as a heuristic search method (Eiben, Smith, 2003).

Genetic representation of solution domain for genetic algorithm stands for development of such data structure, which is suitable for computational processing and at the same time capable to encode solution candidate. The author uses integer type of genes in order to encode number of instances of particular agent within the solution (see figure 4).

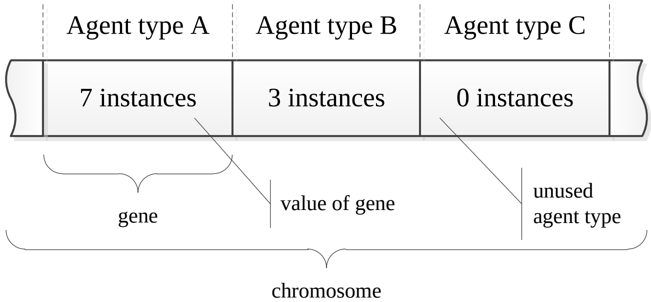

Figure 4. **Genetic representation of solution domain**

Fitness function for genetic algorithm stands for a numeric figure of merit, which is applied to each solution candidate within the genotype. The fitness value expresses the performance of an individual with regard to the current optimum so that different individuals can be compared. The author uses the estimation of the total costs of ownership (TCO) as a core criterion for evaluation of solution candidates. Two positions of TCO are distinguished (Komasilovs, 2012a): 1) investment costs and 2) operating costs.

Investment costs concept stands for such spending which is required to create a robotic system for particular mission. Investment costs defines all expenses required to design, implement and deploy multi-robot system from the scratch into production environment and do not include expenses related to the operation of the system (see figure 5).

Operating costs concept stand for the expenses which are needed to perform particular mission. Operating costs of the multi-robot system is highly dependent on application peculiarities of the system. According to assumption the operating costs include such positions as energy, maintenance and eventual replacement expenses (see figure 6).

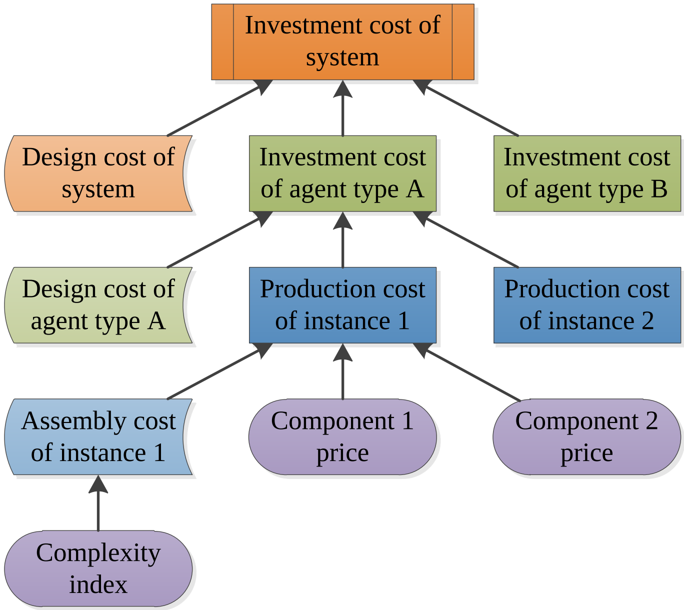

Figure 5. **Graphical representation of investment costs estimation model**

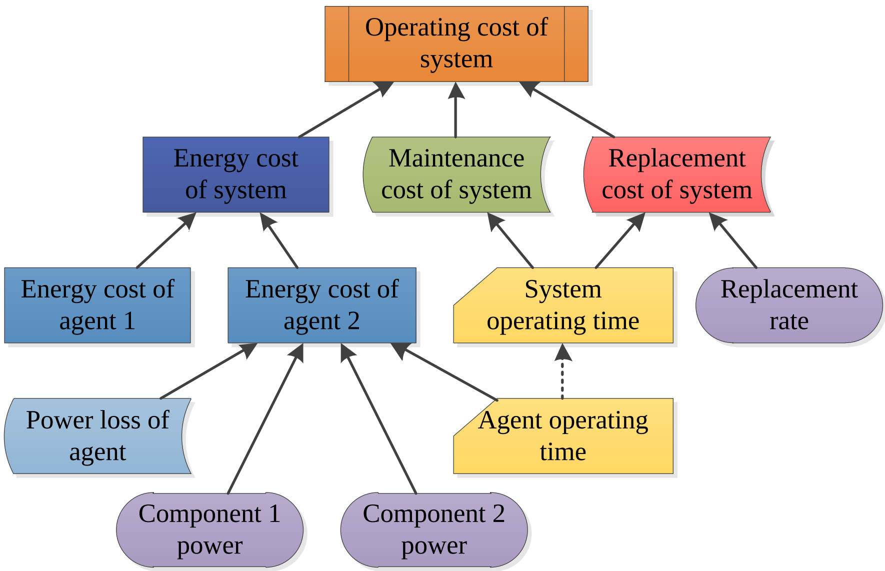

Figure 6. **Graphical representation of operating costs estimation model**

Specialized software *GAMBot-Eva* was developed by the author within the current research for initial evaluation of specifications of multi-robot system. The software provides functionality which supports execution of 5th step of the proposed procedure and performs heuristic search in wide solution domain. The software uses *JGAP – Java Genetic Algorithms and Genetic Programming Package* (Meffert et al., 2012) as a kernel for genetic processing. M*ySQL* database and its client side JDBC drivers are used for persistence storage facilities. Software source code is available on public project site (Komasilovs, 2012b).

The software is designed in a way to allow asynchronous processing of multiple populations of genetic algorithm on the dedicated computing server. The architectural design of the system includes three concepts as follows (see figure 7):

- ✓ processing module, which executes genetic algorithm and manages evolution of its population;
- ✓ presentation module, which provides an user interface for viewing processing results;
- ✓ storage module, which ensures persistent data storage and exchange between first two modules.

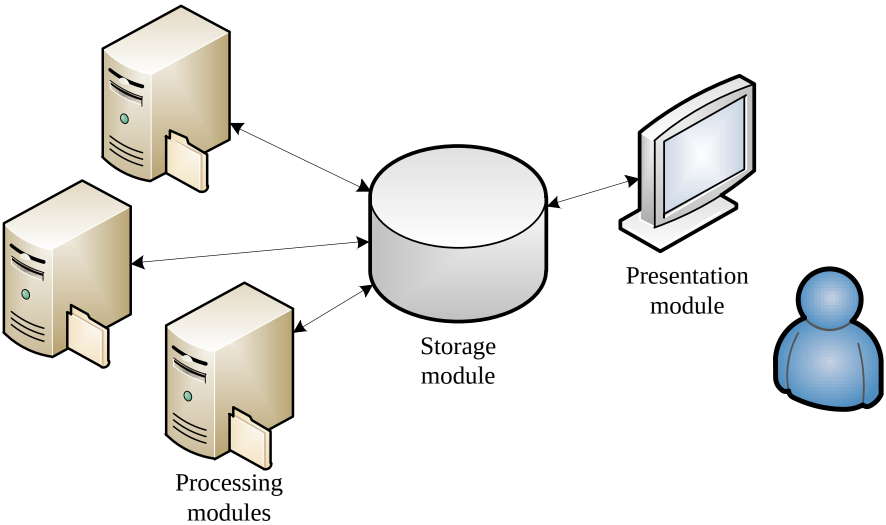

Figure 7. **Architecture of *GAMBot-Eva* software**

6. SIMULATION BASED EVALUATION

The final computational phase (step 6) of the specification optimization procedure stands for simulation based evaluation of small number of multi-robot specification solution candidates. The main goal of this step is to reproduce an environment close to real-world situation and to test selected solution candidates in it. The simulated environment is intended to avoid the development of a real robotic system for tests.

The setup of the simulation environment implies development of models for all agents of the considered multi-robot system as well as a model for the environment of the mission. The author has used *Player/Stage* software bundle as a simulation package, which is an open-source software set developed within *The Player Project* is widely used for multi-robot and distributed sensor research (Gerkey et al., 2003).

The simulation software has highly flexible and extendable architecture, uses simple configuration based on model primitives, and provides low-level access to simulated devices.

In order to support the development of control system for simulated agents the author has created special framework *SiMBot-Ctr*. In general the framework is an abstract tool for creating control systems based on subsumption architecture (see figure 8). The framework allows quick and easy setup of a control system using generic and abstract classes. Also it provides parameterized implementations of most common behaviors of robots. A control system is constructed from ready to use blocks, thereby supporting quick prototyping.

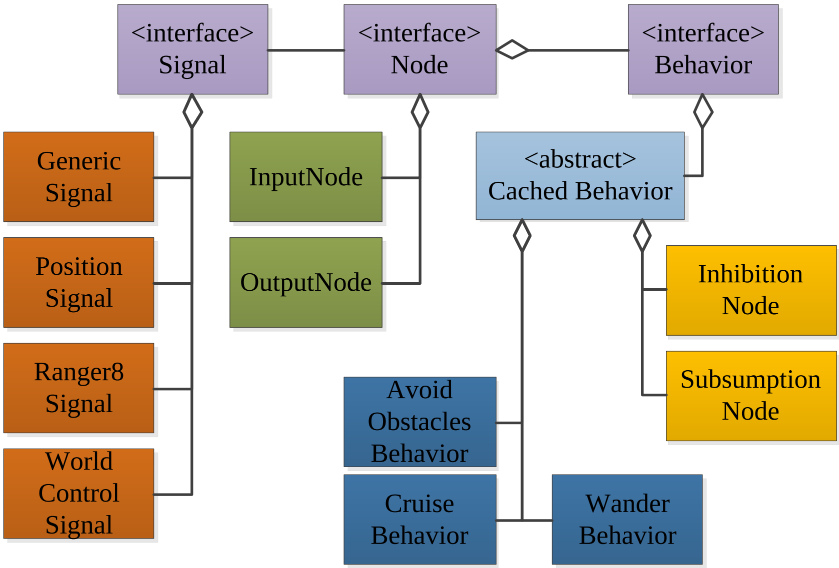

Figure 8. **Conceptual design of *SiMBot-Ctr* framework**

The rationality of the requested fidelity of the simulation based evaluation should be analyzed taking into account that development of the model itself is an expensive and complex process. The reactive architecture of the robot control system implemented within the framework demonstrates acceptable performance. However, a need for the additional system-wide intelligent planning is identified.

Development of highly detailed simulated environment as well as implementation of intellectual control system for simulated agents is considered as out of the scope of the thesis.

The author sees the possibility to use the robotic system implemented using a real hardware for fine tuning of the specification optimization procedure. Practical hardware implementation of grass mowing agents is started within the master's thesis supervised by the author. Field experiments with the working prototype of autonomous grass mower with steering and GPS system are running.

CONCLUSIONS

Major results of the thesis

A procedure for optimization of a specification of heterogeneous multi-robot system within the full solution domain is developed. The objectives of the thesis are fulfilled.

1. *There is performed an analysis of specification development methods applied for heterogeneous multi-robot systems.*

During the analysis actual research directions in the field of multi-robot systems were considered. The author revealed that most of modern investigations are aimed to development and fine tuning of working solution for particular task. However there are almost no researches focused on formal and universal method development for multi-robot systems.

The author found that high level design of multi-robot systems is not proved by any examination but instead is based on the facilities available during the research. Thereby, the author raised specification development problem as unsolved aspect of multi-robot system.

2. *Optimization task and solution concept of specification of heterogeneous multi-robot system is defined.*

The definition includes criterion, constraints and parameters for the optimization. The author has selected the total costs of ownership as the integral optimization criterion for practical experiments, taking into account application peculiarities of robotic systems.

The concept of solution for aforementioned optimization task was defined using three major terms: solution, agent, and component. The solution is defined as a set of agents. The agent is the unit of the system, either, mobile robot or stationary device. Agents are composed from the components, the indivisible concepts of the system which define particular functionality but not its implementation.

3. *The procedure for finding optimal specification of heterogeneous multi-robot system in full solution domain is developed.*

The procedure has iterative nature and consists of eight consecutive steps. First the business requirements are defined, which are then decomposed into the concepts of the solution. Next, the solution domain is analyzed and various evaluation methods are applied to solution candidates. Finally, the optimization results are analyzed and, if it is required, the definition of the mission is refined starting another iteration of the procedure.

4. *Mission definition technique for heterogeneous multi-robot systems and the approach for decomposition of the mission are developed.*

According to the proposed concept of the specification optimization procedure the mission for multi-robot system is defined using the list of components, required for the accomplishing the mission. Classification principles for components, their structural and dynamic properties are defined.

5. *The size of feasible solution domain of the specification optimization task is analyzed.*

Special methods are developed to find the number of unique agents and the number of their possible combinations. The custom *CoMBot-Gen* software was developed to perform analysis of agent combinations and eliminate invalid combinations. Near double exponential growth of number of solutions as a function of the number of defined component is found.

6. *Heuristic search algorithm for initial evaluation of specifications of multi-robot system is implemented and experimentally tested.*

Modular software *GAMBot-Eva* for genetic algorithm based heuristic search is developed. The software is used as a universal tool for the initial evaluation of the solution candidates. Implementation of the genetic algorithm includes development of the genetic representation of the solution domain, development of the fitness function used to estimate the total costs of ownership. Successful practical experiments are performed to test various aspects of the initial evaluation of solution candidates.

7. *Possibility to use simulation techniques for fine evaluation of specification of multi-robot system is analyzed.*

Practical experiments with the developed *SiMBot-Ctr* framework confirm the possibility for detailed evaluation by simulation techniques. It is important to assess the necessary level of details of the model because the development of the model and the simulation experiments are complicated and time consuming.

Conclusions and development prospects

Formal analysis and prediction of utilization of various functions of the multi-robot system are not being investigated within the multi-robot research domain. Properly designed multi-robot system requires fewer investments from a customer and at the same time it is capable to provide performance and fault tolerance required for completing the mission defined for the system.

The procedure is proposed for the optimization of the specification of multi-robot system. It defines a workflow for resolving the optimization task and includes business requirement specification, mission decomposition into components, solution domain analysis, solution candidate evaluation using heuristic algorithms and simulated models.

Analytical estimation of the number of feasible combinations of the agents reveal near double exponential growth of number of solutions as a function of the number of defined component for the specification optimization task.

There are improvements for proposed specification optimization procedure which are recommended for implementation but at the same time are out of scope of the thesis. The author recognizes following development prospects:

- ✓ to improve the model of components and their properties in order to allow more flexible definition of their investment and operating expenses;
- ✓ to implement the estimation model for the total costs of ownership using modern estimation and planning methods defined in the field of economics;
- ✓ to increase parameterization degree of the developed optimization software thus expanding application possibility;
- ✓ to developed universal concept for defining tasks of the mission for robotic system thereby making implementation of the optimization procedure more versatile;
- ✓ to introduce an additional fast simulation step to the optimization procedure alongside with final evaluation step;
- ✓ to extend the framework for the control of the simulated multi-robot system allowing operational planning facilities;
- ✓ to make the optimization process in general and its software implementation more interactive and continuous allowing greater control over optimization peculiarities and the final result;
- ✓ to analyze the application of proposed specification optimization procedure in the other areas to spread the approach and, vise-versa, to get knowledge and methods from external areas.

LITERATŪRAS SARAKSTS

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