Rational Cooperative Agents in Open Environments

Matthias Klusch
Deutsches Forschungszentrum für Künstliche Intelligenz
klusch@dfki.de

Outline

- Cooperation and Agents
  - Nature and Models
- Rational Cooperation in Stable Coalitions
  - Security, Trust, Dynamics
  - Related Research and Development
- Cooperative Agents Tomorrow and Beyond
  - Semantic Web Service Coordination
  - Quantum Based Cooperation
Cooperation in Modern Computing Environments

Communication + Coordination + Joint Problem Solving

? Rationality of cooperative behavior

Kloesch  DFKI 24.6.2004  3

Cooperation Models for Agents: A Brief History

Since 1980's: Rationality of cooperative behavior regulated by

- **Principle of full satisfaction of shared goals.**
  
  "If an agent has knowledge that one of its actions will lead to one of its goals, then the agent will select that action."

1989: Partial global planning (Durfee & Lesser)
1990: Collective intentional behavior (Cohen & Levesque; Jennings)
1996: Shared Plans operators w/o explicit communication (Grosz & Kraus)

- **Differential in the utility help provides to the individual and group.**
  
  Around 1996: Decision-theoretic planning (Haddawy & Hanks), Teamwork (Tambe)

Kloesch  DFKI 24.6.2004  4
Cooperation Models for Agents: A Brief History (2)

Since 1944: Economically rational cooperation
Economic models for resolving conflicts of interests in sharing joint values between \( N \geq 2 \) self-interested players with non-/transferable utility.

Since 1993: Economic models applied to software agents
- Incentive Contracting, Levelled Commitments (Sandholm)
- Auctions (Sandholm; Jennings)
- Market-Oriented Programming (Wellman)
- Strategic Negotiation (Rubinstein; Rosenschein; Kraus)
- Coalition Forming (Kraus; Shehory; Sandholm; Klusch)

Rational Cooperation in Stable Coalitions
Economically rational agents negotiate game-theoretically stable coalitions to share created joint values while maximizing their benefits.

- **Cooperative game** \((A, v)\)
  - Set \( A \) of agents; Real-valued coalition value function \( v \) assigning each coalition \( C \) its maximal joint value \( v(C) \)

- **Stable solution** \((S, u)\)
  - Coalition structure \( S = \text{Partition of} \ A \)
  - Stable payoff distribution \( u \) of coalition values to individual agents:
    - Shapley value, Core, Stable Set, Nucleolus, Kernel, etc.
  - Efficient, individual rational \( u(\{a\}) \geq v(\{a\}) \)

- **Negotiation of stable solutions**: Coalition forming algorithms
Major Research Challenge

Dynamic negotiation of secure, and trusted stable coalitions among economically rational agents in open environments.

? Dynamics
Security
Trust

Application-oriented research and development at DFKI

Application: Agent Coalitions in Virtual Malls

Economically rational cooperative agents in e-markets form ....

- Retailer agent coalitions
  .... To maximize individual benefits of joint sales to their customers
- Customer agent coalitions
  .... To maximize individual benefits of joint purchases at retailer site, or
  .... To maximize individual brokerage commission from their users
- Mixed coalitions

Coalition Games (A, v)
Stable Solutions (S, u)
**Example: Retailer Agent Coalition Game**

Local items:
car\(_{11}\), car\(_{12}\), car\(_{13}\)

**Item Sales:**
- **car\(_{11}\):** 2 k€
- **car\(_{22}\):** 1.5 k€
- **car\(_{32}\):** 1 k€

Local items:
car\(_{21}\), car\(_{22}\), car\(_{23}\)

- **car\(_{21}\):** 1.5 k€
- **car\(_{12}\):** 1 k€
- **car\(_{31}\):** 1 k€
- **car\(_{33}\):** 2 k€

Local items:
car\(_{31}\), car\(_{32}\), car\(_{33}\)

- **car\(_{31}\):** 1 k€
- **car\(_{12}\):** 2 k€
- **car\(_{13}\):** 2 k€
- **car\(_{21}\):** 2 k€
- **car\(_{23}\):** 2 k€

Coalition values \(v(C)\): Maximum car sales in \(C\)

**Coalition Game \((A,v)\)**

\[
\begin{align*}
v(a_1) &= 2, \quad v(a_2) = 1.5, \quad v(a_3) = 1 \\
v(a_1,a_2) &= 6, \quad v(a_1,a_3) = 8, \quad v(a_2,a_3) = 7 \\
v(a_1,a_2,a_3) &= 15
\end{align*}
\]

**Kernel Stable Coalitions**

Kernel stable payoff distribution \(u\) of coalition values \(v(C)\) to agents in coalition structure \(S\) pairwisely balances agents’ potential surpluses \(s(a,a')\) in alternative coalitions not in \(S\).

**“I can obtain more in alternative coalitions without you, than you without me.”**

Kernel of \((A,v)\):
Set of all configurations \((S,u)\) with \(a, a' \in C \subseteq S\):

\[
\begin{align*}
s(a,a') &= s(a',a), \quad \text{or} \\
s(a,a') &> s(a',a) \quad \text{and} \quad u(a') = v(a'), \quad \text{or} \\
s(a,a') &< s(a',a) \quad \text{and} \quad u(a) = v(a)
\end{align*}
\]

Surplus \(s(a,a')\) of agent \(a\) over \(a'\) in all alternative coalitions not in \(S\):

**Maximum excess** \(e(C) = v(C) - u(C)\) of coalition \(C\) not in \(S\), \(a\) in \(C\), but \(a'\) not in \(C\).
Example: Kernel Stable Retailer Agent Coalition

Local items:
car_{11}, car_{12}, car_{13}

Car sales:
\begin{align*}
car_{11}: & 2 \text{k€} \\
car_{22}: & 1.5 \text{k€} \\
car_{32}: & 1 \text{k€}
\end{align*}

\begin{align*}
v(a_1) &= 2, \quad v(a_2) = 1.5, \quad v(a_3) = 1 \\
v(a_1,a_2) &= 6, \quad v(a_1,a_3) = 8, \\
v(a_2,a_3) &= 7, \quad v(a_1,a_2,a_3) = 15
\end{align*}

S = \{a_1, a_2, a_3\}, \quad u = (5, 4.25, 5.75)

Negotiation of Kernel Stable Coalitions

KCA (Klusch & Shehory, 1996)

Each agent \( a \) in \( C \) of coalition structure \( S \) with payoff distribution \( u \):
- Broadcast local items, and maximum contribution \( l_{\text{worth}}(a,C) \) for all \( C \) in \( S \)
- If coalition leader of \( C \) then
  - a) Exchange beneficial Kernel stable proposal \((S',u')\) for each \( C+C' \)
  - b) Evaluate and accept most beneficial incoming proposal
  - c) Broadcast decision to other agents; Stop if no agent accepted any proposal
  - d) Decide on one bilaterally accepted proposal as next configuration \((S',u')\)

? Preserve local data privacy in coalition negotiations without any loss of benefit
**KCA: Privacy Preserving Coalition Negotiation**

Thrm (Klusch & Blankenburg, 2004):

KCA based coalition negotiations are safe against non-disclosure of self-values \( v(\{a\}) \).

**Basic idea:** Hiding of self-value \( v(a) \) of \((A,v)\) induces new game \((A,v')\)

- new K-stable solution \((S,u')\) balancing *unchanged* surplus values
  
e.g. for \( S = \{(a,a_j), a_k\} \): \( s'(a,a_j) = (v(\{a,a_j\}) - v(a_j)) - ((u(a) - v(a)) + u(a_j)) = s(a,a_j) \)
- Payoff distribution \( u' = u \) with \( u'(a_j) = u(a) - v(a) \). Equivalent games.

Local data exclusively used to compute local profits \( v(\{a\}) \)
can be hidden from other agents in KCA based coalition negotiations 
without loss of benefit for anyone.

---

**KCA: Safe Negotiations in Open Environments?**

**Safe** against use of imperfect coalition values \( v(C) \)

- *Estimated crisp coalition values* \( v(C) \) lead to different games \((A,v')\)
  for which K-stable solutions assign lower payoffs to the estimating agent.
- Modified coalition algorithm KCA-F for forming fuzzy K-stable coalitions 
  with *fuzzy coalition values*

**Not safe** against fraud and dynamic changes of the environment

- Full re-start of KCA coalition negotiations required.
- Agents can unfoundedly strengthen their bargaining position by frauds, 
  but at very high computational costs.

Deceiving Other Agents in Coalition Negotiations

- Delay communication of own local values lworth(a,C) to other agents.
- Predict K-stable solution (S,u) of given game (A,v) by simulation.
- Determine maximum fraud r for alternative coalitions C’ not in S.

\[ r = \arg\max_r \{ u'(a) | K\text{-stable} (S',u') \text{ of } (A,v'), C' \text{ not in } S', v'(C') = v(C') + r \} \]

- Communicate local values including fraud lworth'(a,C') = lworth(a,C') + r

Trust in coalition negotiations.
Computational efficiency of stable solutions.

Bilateral Shapley Value Stable Coalitions

- Shapley value of agent in grand coalition C=A

\[ u(a) = \sum_{C \subseteq A} \frac{(|C| - |A|)!|C|!}{|A|!} \left( v(C) - v(C \setminus \{a\}) \right) \]

- Bilateral Shapley value for arbitrary coalitions C (Klusch, 1997)

\[ C = C_1 \cup C_2, \quad C_1 \cap C_2 = 0 \]

\[ BSV_c(C_1) = \frac{1}{2} v(C_1) + \frac{1}{2} (v(C) - v(C_2)), \quad BSV_c(C_2) = \frac{1}{2} v(C_2) + \frac{1}{2} (v(C) - v(C_1)) \]

- Recursive computation of payoffs BSV_c(a) over coalition history tree of C
- Fair and individual rational for super-additive games
Example: BSV-Stable Retailer Agent Coalition

Local items
- car_{11}, car_{12}, car_{13}
  - car_{11}: 2 k€
  - car_{22}: 1.5 k€
  - car_{32}: 1 k€

Local items
- car_{21}, car_{22}, car_{23}
  - car_{21}: 1.5 k€
  - car_{12}: 1 k€
  - car_{31}: 1 k€
  - car_{33}: 2 k€

Local items
- car_{31}, car_{32}, car_{33}
  - car_{13}: 1 k€
  - car_{12}: 2 k€
  - car_{13}: 2 k€
  - car_{21}: 2 k€
  - car_{22}: 2 k€

\[ v(\{a_1\}) = 2, \]
\[ v(\{a_2\}) = 1.5, \]
\[ v(\{a_3\}) = 1, \]
\[ v(\{a_1, a_2\}) = 6, v(\{a_1, a_3\}) = 8, \]
\[ v(\{a_2, a_3\}) = 7, v(\{a_1, a_2, a_3\}) = 15 \]

Trusted Agents and Coalitions

**Trust rating** of agent \( a^* \) for \( a \) in joint coalition \( C \):

- Sum of changes of payoff \( u(a) \) caused by \( a^* \) in past joint coalitions
  - Agent \( a^* \) breaks joint coalition with \( a \)
  - Utility of items provided by \( a^* \) to \( a \) changes unexpectedly
  - Trust ratings of \( a^* \) by all other agents in \( C \) (Reputation of \( a^* \) in \( C \))

Cooperative behavior of \( a^* \) observed by \( a \) during probation time.

Trustworthiness of coalition \( C \): Sum of trust ratings of its members.
**Dynamic and Trusted Coalition Forming**

**BSCA-T** (Park/Klusch, 2004)

Each agent $a$ in $C$ of coalition structure $S$ with payoff distribution $u$:

- Communicate local values and individual trust ratings

If coalition leader of $C$ then

- Determine BSV-stable and trustworthy joint coalitions $C$
- Exchange, evaluate received proposals from trustworthy coalitions $C'$
- Form bilaterally accepted most beneficial merger $C+C'$
- Determine new overall bilateral coalition configuration $(S',u')$
- React on changes using coalition history tree (split if agents leave)

Update individual trust rating of agents within their probation time.

---

**Evaluation Results**

**Avg. total agent payoffs**

- **Vs. Negotiation round times**
- **Vs. Number of untrustworthy agents**

Each simulation $(n=30/40/50/60)$ agents; $n*100$ negotiations

Initial probation time = 4 negotiations; Fixed set of simulated changes
Secure Data Mining in Stable Agent Coalitions

KDEC clustering scheme (Klusch/Lodi/Moro, 2003)
- Coalition members communicate additive samples of Kernel-based local data density estimates to their coalition leader.
- Receive sampled global data density estimate.
- Local data clustering on reconstructed GDE.

\[
\varphi_{K,h}^{GDE}(\mathbf{x}) = \sum_{i=1}^{N} \frac{K(d(x,i))}{h} \in \mathbb{R}^n
\]

Dynamic Coalition Forming for Resource Allocation

DCF-S scheme (Gerber/Klusch, 2003):
- Capability-based re-allocation in re-organising coalitions.

Rational simulation of suitable coalitions
- Random agent selection, or
- Probabilistic reasoning on agents' capabilities, or
- Adaptive capability based clustering of agents (SVM)

Asymptotic stability (#task re-allocations over time)

Evaluation Results

Summary of Contributions

Rational cooperation in
- Dynamic
- Secure
- Trusted
coalitions in open environments

Cooperative applications
- e-trading
- resource allocation
- power transmission planning

BMBF research project SEMAS (Secure Multiagent Systems), 2001 - 2003.
Implemented Cooperative Agent Systems

Mobile timber trading via auctions, and dynamic joint timber production planning  

Mobile and dynamic resource allocation planning for cereal harvesting.  

Online trading via English, Dutch, and Vickrey auctions with integrated remote payment service.  

Future Research and Development

- Field trial of cooperative agents for dynamic resource allocation in cereal harvesting  
  Regional Saarland/Rhineland-Palatine project AGRICOLA-II (2004 – 2005)

- Cooperative agents for flexible Semantic Web service coordination in mobile P2P computing environments  
  National BMBF research project SCALLOPS (2004 – 2006)  
  European commission FP6 IST research project CASCOM (2004 – 2006)

- Cooperative quantum computational agent systems, and applications  
  European Commission FP6 IST FET research initiatives (2005/2006+)
2006: Flexible Semantic Web Service Coordination

Service Composition
Planning and Execution

- Fast (re-) planning of composite OWL-S answer services
- Consistent execution in mobile P2P computing

Service Negotiation

- Dynamic and trusted
- Service agent coalitions
- Security policies

Service Discovery

- Dynamic and trusted
- Relaxed matching
- Security constraints

BMBF research project SCALLOPS (2004 - 2006)

2020: Cooperation in the Quantum Computing Age

- Exploitation of the power of quantum computing and communication by cooperative agents on networked hybrid quantum computers.

- Fundamentals of Quantum Physics

  Complementary particle-wave behavior of quantum objects
  Superposed quantum state (linearity, parallelism)
  Measurement (decoherence, uncertainty)
  Unitary evolution (reversible computing)
  Entanglement (non-locality)
Quantum Computing and Communication

- Qubit: \( |\psi\rangle = \alpha|0\rangle + \beta|1\rangle \), \( p(0) = |\alpha|^2 \), \( p(1) = |\beta|^2 \), \( |\alpha|^2 + |\beta|^2 = 1 \)
- Quantum parallelism: 
  \[
  U \left( \frac{1}{\sqrt{2^n}} \sum_{x=0}^{2^n} |x\rangle |0\rangle \right) = \frac{1}{\sqrt{2^n}} \sum_{x=0}^{2^n} |x\rangle |f(x)\rangle
  \]
- Unitary quantum logic gates, and quantum algorithms
  - Polynomial factorization of integers (Shor, 1994), quantum cryptography
  - Quadratic speed-up of searching unordered lists of items (Grover, 1996)
- Entanglement as computational resource
  - Instantaneous correlated state change of spatially separated entangled qubits
  - Physically secure communication (Teleportation; Dense coding; No-cloning)

Cooperative Quantum Computational Agents

- Faster cooperative search and service discovery.
- Reduced, physically secure inter-agent communication.
- Instantaneous propagation in hybrid quantum computer networks.
- Mutual trust required.
Special Thanks To

Dr. Steve Allen
Bastian Blankenburg
Josenildo Costa da Silva
Ovidiu Drugan
Dr. Klaus Fischer
Patrick Frotscher

Andreas Gerber
Nils Kammenhuber
Dr. Helmut Lohmann
Helena Maria Pereira Nunes
Wooseok Park
Carsten Tichy

Prof. Jörg Siekmann