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A resilience by teaming framework for collaborative supply networks

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ABSTRACT

Supply network resilience is an emerging concept related to the ability of a network to tolerate disruptions; current understanding of its meaning and dimensions, its role in the design and operation of supply networks, and its relation to sustainability is at its early stages. Existing approaches are based on the trade-off between increased resources and higher fault-tolerance. The Fault Tolerance by Teaming (FTT) principle of Collaborative Control Theory has been applied in sensor networks effectively and appears as a promising original approach not based on the aforementioned trade-off and capable of producing networks with higher resilience.

Inspired by the FTT principle, a *Resilience by Teaming Framework* (RBT) for supply networks is developed to address the design and operation of resilient supply networks. RBT is tested and validated through the application of its protocols to case studies in production and distribution networks. Evidence from case studies' results suggests that through FTT-based protocols and RBT it is possible to achieve higher fault tolerance with fewer resources than under traditional approaches.

1. Introduction

Supply networks (SNs) can be defined as a collection of autonomous agents with self-interested goals that interact to enable physical, digital or service flow through a series of links. SN agents' interactions constitute a form of e-Work, defined by Nof (2003) as *any collaborative, computer-supported and communication-enabled productive activities in highly distributed organizations of humans and/or robots or autonomous systems*. Over time, e-Work systems, such as supply networks, have gained significant scale and complexity, and negative interactions among components become difficult to prognose, anticipate, and/or avoid. These hidden interactions can possibly lead to disruptions affecting individual agents as well as larger collections thereof; therefore, resilience emerges as an important area to explore within complex adaptive systems research.

Despite the fact that the meaning of resilience is still being molded, various authors propose different frameworks to create resilient supply networks, as shown in Table 2. Their approaches diverge in several directions and vaguely overlap, in part, because of the lack of agreement on underlying resilience principles. Moreover, several approaches are based on trade-offs between quality of service (QoS) and number/type of resources used. Selecting alternatives with increased tied-up capital, in the form of storage, excess capacity, and/or increased agent reliability, enables higher fault-tolerance; however, as SNs become more complex, these approaches affect their long-term sustainability.

Over the last decades, several researchers have collaborated to develop and refine a set of six principles to design e-Work systems, leading to the emergence of Collaborative Control Theory – CCT (Nof, 2007). Although each of the CCT principles can have a meaningful impact on the design and control of resilient SNs, the principle of collaborative fault-tolerance or Fault-Tolerance by Teaming (FTT) stands out as a potential enabler of resilient performance among agents susceptible to disruptions.

FTT principle is based on the notion that a team of weaker agents can outperform single flawless agent by enabling smart automation to overcome (temporarily) faulty agents (Nof, 2007; Velásquez & Nof, 2009). Although necessary for resilience, fault-tolerance is not a sufficient condition for resilient SNs (Sterbenz et al., 2010). Fault tolerance is a static condition relative to the structure of a network but does not include active defenses and responses also required to be resilient (e.g., the use of situation awareness and predictive models to anticipate possible future disruptions and the protocols required to actively re-configure the network based on these observations to minimize/avoid the impact of such disruptions). Nevertheless, the fundamentals of FTT (Table 1), combined with notions from the Conflict and Error Detection and Prognostics (CEDP) principle of CCT – which calls for the use of automated mechanisms for situation awareness to

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Nomenclature

a, i, j, k	supply network agent
A	set of supply network agents a
a_u	agent responsible for delivering D_u
$b_{i\to j}$	bid submitted by i to source agent j
$cl_{i\to j}$	communication link between i and j
CN	communication network
$Cost\left[\delta_{i\to j}\right]$	delivery cost under path $\delta_{i\to j}$
CP_a	control protocols of agent a
$\mathbb{D}$	set of disrupted states of an IRN
D_u	flow delivery agreed between i and j
d_{min}^{GEO}	minimum distance between agents to avoid proximity-correlated disruptions
$deg^{IN}(a)$	in-degree of agent a
$fl_{i\to j}$	flow link connecting agent i to agent j
$Flex\left[\delta_{i\to j}\right]$	path $\delta_{i\to j}$ flexibility
$ft_{h\to h'}$	time to deliver flow from h to h'
FN	flow network
FR_a	set of fuzzy scoring rules of agent a
$GO\left[P_a^1\right]$	index of topographical overlap for P_a^1
h	intermediary agent in $H_{i\to j}$
$H_{i\to j}$	set of intermediaries between i and j
$p(r^P)$	probability r^P is available during Δt
$p(\phi[r]\in\mathbb{D})$	threshold probability to consider resource r at risk of disruption within Δt_{ECDT}
$p(\phi[r](t+\Delta t_{ECDT})\in\mathbb{D})$	disruption probability prognostic for r within Δt_{ECDT}
$p_{NB}(r^P)$	probability r^P is not blocked
$p_{NS}(r^P)$	probability r^P is not starved
P_a	set of predecessors of agent a
P_a^1	set of predecessors of agent a in T1
P_a^2	set of predecessors of agent a in T2
Q	initial flow quantity request from agent a to agents in P_a^1
Q_u	flow quantity to be delivered in D_u
$Q_{i\to j}$	flow quantity agent i bids (or agrees) to source agent j in $b_{i\to j}$
Q_{SG}	size of sourcing gap SG
Q_t	quantity of flow stored by a at time t
$\mathrm{QoS}_{i\to j}$	QoS delivered to agent j by agent i
$\mathrm{QoS}_{i\to j}^{SLA}$	QoS target for flow between i and j under SLA
r	resource in R_a
r^P	process type resource in R_a
r^S	storage type resource in R_a
R_a	internal resources of agent a
S_a	set of successors of agent a
$Score$	rating of path $\delta_{i\to j}$
SFS	sourcing flow schedule
SG	sourcing gap
SG_{to}	time-out for re-submitting a sourcing request for an unfulfilled SG
$Slack\left[\delta_{i\to j}\right]$	delivery time margin under path $\delta_{i\to j}$
$ST1P_{to}$	time-out for ST1P execution
t	time
$t_{b/w\ fail}\left[r^P\right]$	cumulative probability for time between failures for r^P
$t_{down}\left[r^P\right]$	downtime duration distribution for r^P
$t_{last\ fail}\left[r^P\right]$	last known failure time for r^P
t_u	current delivery time for D_u
t_{u^*}	time of 1st delivery D_u in SFS following sourcing gap SG
$t_{i\to j}$	delivery time agent i bids (or agrees) to source agent j in $b_{i\to j}$
$TL\left[r^S\right]$	target level of storage r^S
$TO\left[P_a^1\right]$	index of topological overlap for P_a^1
TP	throughput
t_{SG}	start time of sourcing gap SG
w	no. of participants in T1
w^*	minimum size of T1 to achieve θ^*
$\Gamma\left(i, d_{min}^{GEO}\right)$	no. of agents within d_{min}^{GEO} of agent i
$\delta_{i\to j}$	path from agent i to agent j
$\Delta_{i\to j}$	set of paths from agent i to agent j
$\delta_{i\to j}^{x^*}$	best path selected by DNF/RP
Δt	time interval
Δt_{ECDT}	prognostic horizon for ECDT
Δt_{ECDT}^{upd}	update frequency of ECDT
Δt_{hzn}	scheduling horizon in ST1P
Δt_i	agent i flow delivery leadtime
Δt_r	leadtime required by agent a to receive flow from another agent
Δt_{SG}^{upd}	frequency of update of SG
$\theta(x, w, \Delta t_r)$	fraction of sourcing requests that can be served by x agents (out of w) within Δt_r
θ^*	probability of receiving at least one bid within Δt_r from an agent in P_a^1
ϑ	capacity of a stage with n processes
$\vartheta[r]$	design capacity of resource r
κ	weight factor of distance to destination in $Flex\left[\delta_{i\to j}\right]$
λ	maximum allowable overlap between any two $D_h\in SFS$, as a fraction of Q
λ_u	overlap between bid $b_{i\to j}$ and a delivery $D_u\in SFS$
$\mu[h]$	flow processing rate at $h\in H_{i\to j}$
$\mu\left[r^P\right]$	flow processing rate of resource r^P
$\mu[S_a]$	flow consumption rate of successors of agent a
ξ	allowable extension of a bid, as a fraction of Q
ρ_a	$Slack\left[\delta_{i\to j}\right]$ threshold set by agent a to re-evaluate delivery path $\delta_{i\to j}$
υ	relative importance of $GO\left[P_a^1\right]$ vs. $TO\left[P_a^1\right]$
$\phi[r]$	a state of resource r
$\Phi[r]$	set of states $\varphi[r]$ of resource r
$\phi[r](t)$	state of resource r at time t
$\phi[R_a]$	a state of an IRN with resources R_a
$\phi[R_a](t)$	IRN state at time t
ψ_i	probability density function of Δt_i
Ψ_i	cumulative distribution function of Δt_i
ω_h	cost of processing flow at $h\in H_{i\to j}$
$\omega_{h\to h'}$	cost to send flow from h to h' in $H_{i\to j}$

Abbreviations

CCT	Collaborative Control Theory
CEDP	Conflict and Error Detection and Prognostics
CLA	cluster network architecture
CONWIP	constant WIP
CPLC	Collaborative Production Line Control
DFCP	Distribution Flow Control Protocol
DNF/RP	Delivery Network Formation/Re-configuration Protocol
DWIP	dynamic WIP
ECDT	Early Conflict Detection Tool
FTT	Fault-Tolerance by Teaming
FTTP	Fault-Tolerant Time-out Protocol
IFCP	Internal Flow Control Protocol
IRN(s)	Internal Resource Network(s)
IRN-CDB	IRN configuration database
LCRP	Lowest Cost Routing Protocol
QoS	quality of service
RBT	Resilience by Teaming
SFCP	Sourcing Flow Control Protocol
SLA(s)	service level agreement(s)
SN(s)	supply network(s)