Overview of UT-SIM Framework and Application Examples

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ExchangeRisk

Acknowledgement

- **Former graduate students**

  Viswanath Kammula, Hu Zhan

- **Current graduate students**

  Saeid Mojiri, Xu Huang, Vahid Sadeghian, Georgios Giotis, Mohamed Sayed Mohamed

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  Canadian Foundation of Innovation: LOF

  Ontario Ministry of Research and Innovation: ERA

  Connaught Fund

- **Industry partner**

  S-Frame

Introduction – Seismic Performance Assessment

Experimental Method

- Static cyclic test of components
  - Predefined loading history
  - Performance of structural elements under cyclic load reversals
- Shaking table test
  - Most complete and accurate method
  - Expensive
  - Limitation in the scale of specimen: long-span bridges, high-rise buildings, large scale soil domain

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- **Numerical Simulation**
    - Best alternative when experiments are not feasible.
    - The accuracy of prediction results depends on the accuracy of the model.

Introduction – Seismic Performance Assessment

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Numerical Simulation

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Hybrid (numerical-experimental) Simulation

- Equation of motion is solved numerically.
- Whole or part of the structural system is tested physically.
- Allows geographically distributed testing.

Introduction – Hybrid Simulation

Equations of Motion

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{R}(\mathbf{u}) = \mathbf{F}(t)$$

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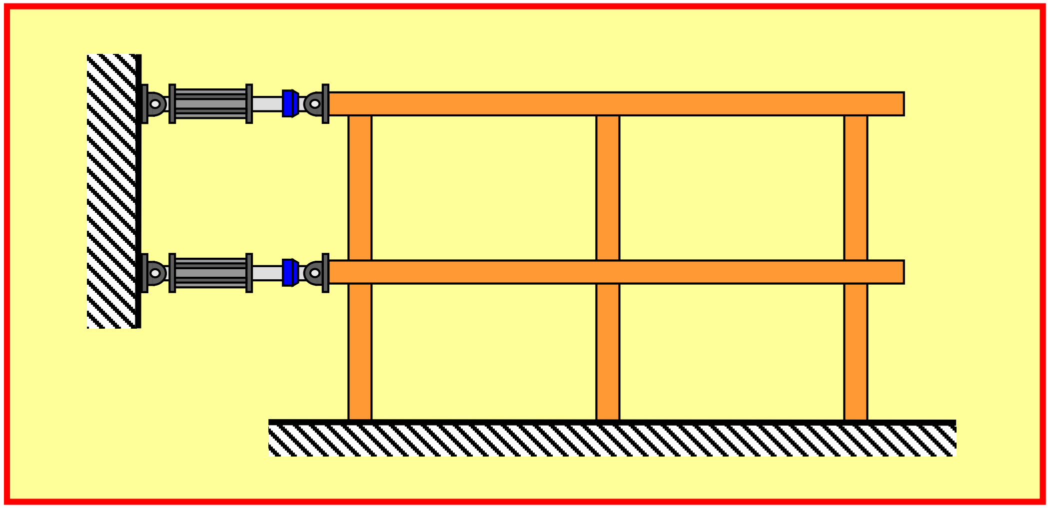

Laboratory Testing

Introduction – Hybrid Simulation

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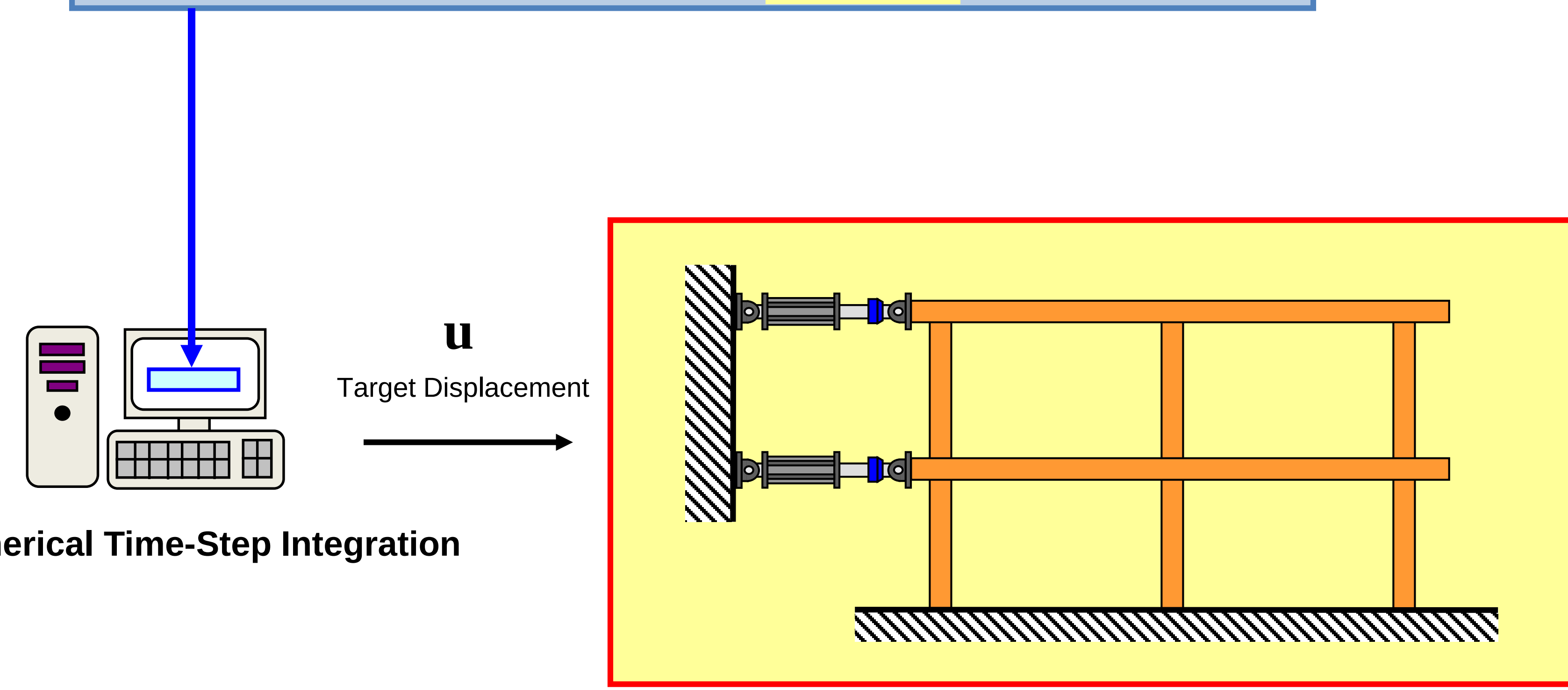


Numerical Time-Step Integration

Laboratory Testing

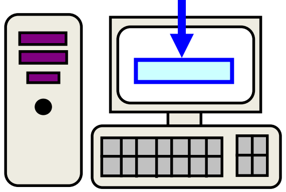
Introduction – Hybrid Simulation

Equations of Motion

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{R}(\mathbf{u}) = \mathbf{F}(t)$$

$\mathbf{R}(\mathbf{u})$

Reaction Force



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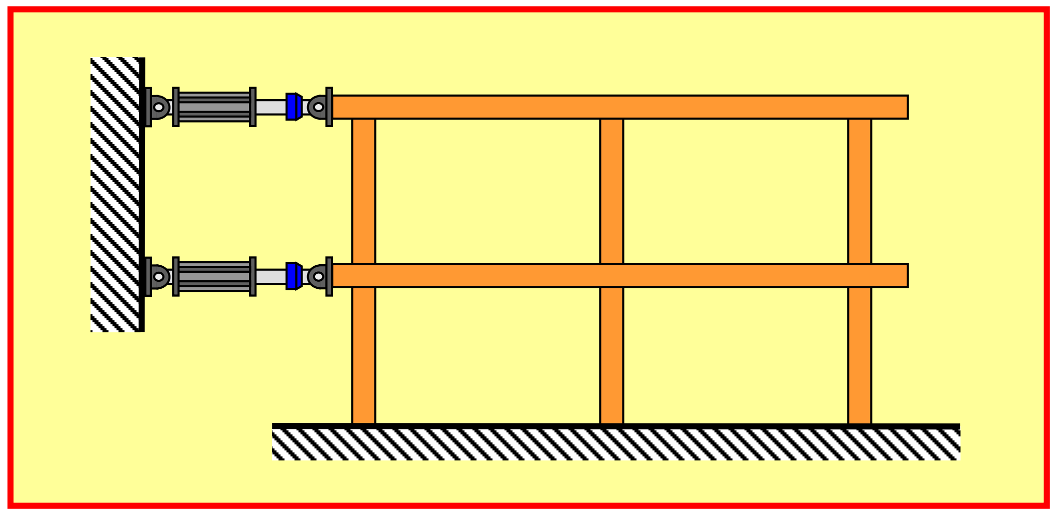
Target Displacement

Numerical Time-Step Integration



Laboratory Testing

Introduction – Hybrid Simulation

Equations of Motion

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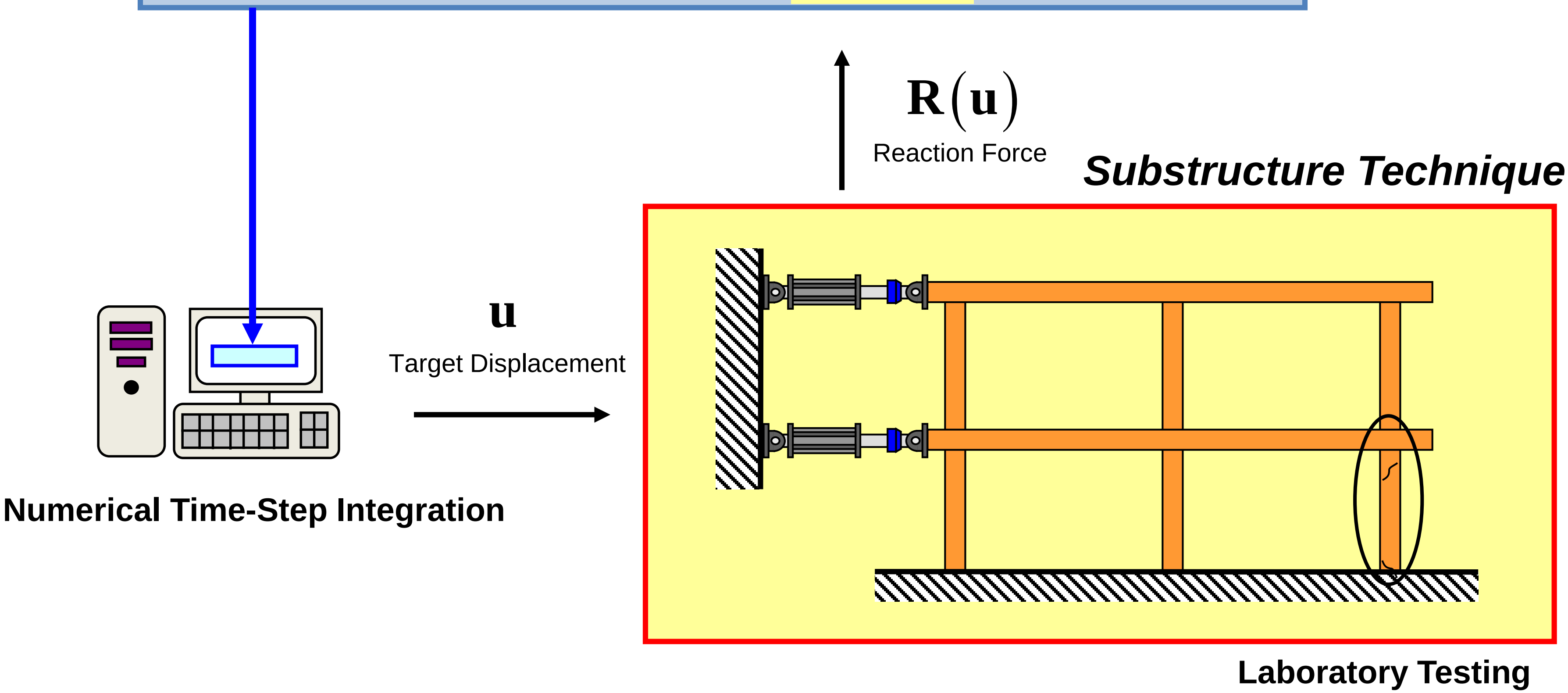

Introduction – Hybrid Simulation

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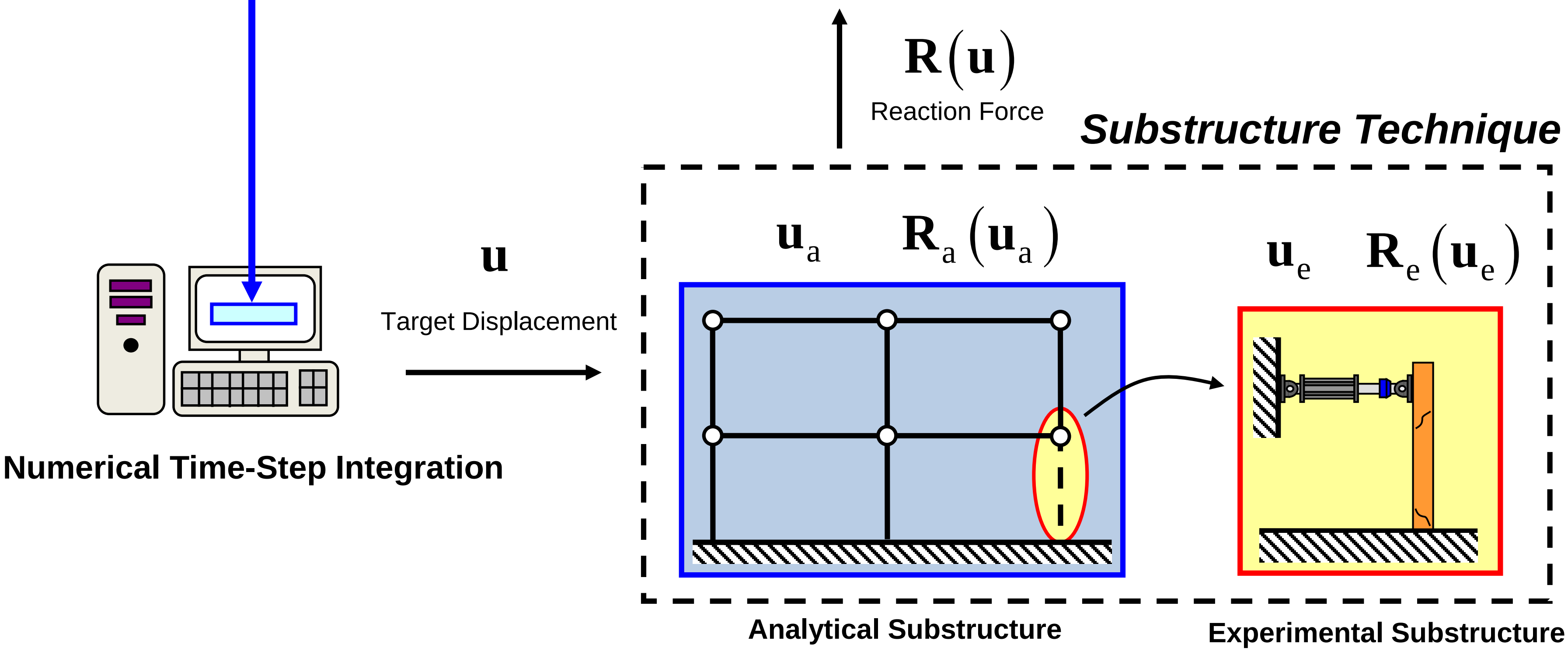
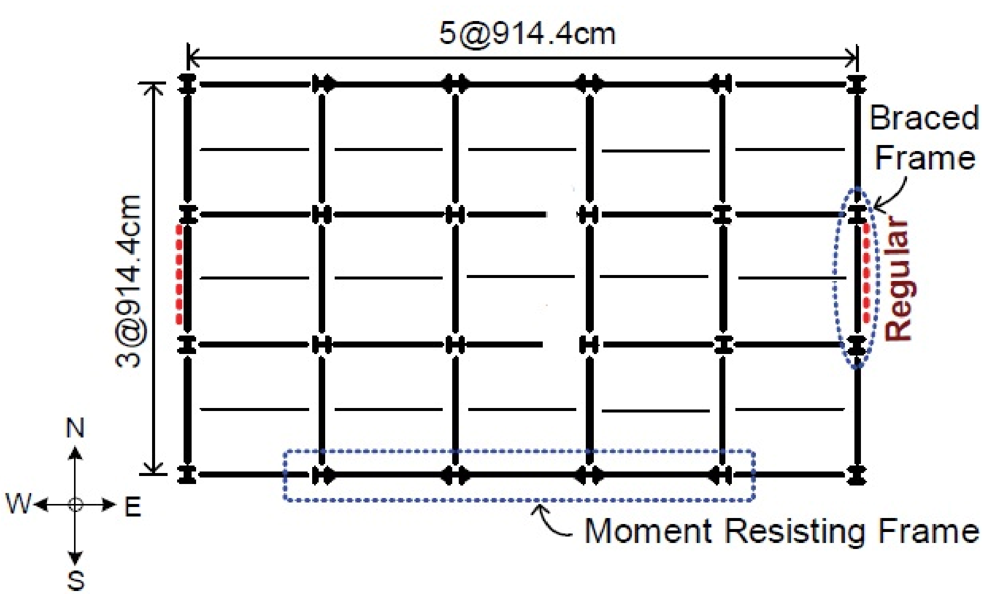
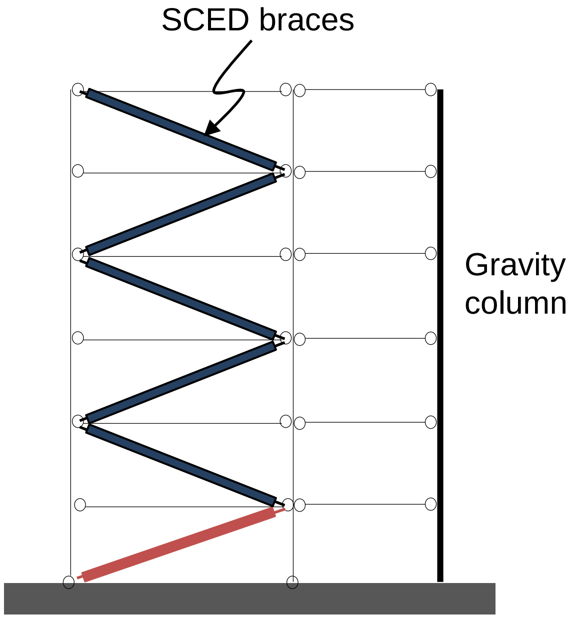


Introduction – Hybrid Simulation

- **Recent Hybrid Simulation Example: Six-storey Steel Frame with SCED Brace**
  - Designed with ASCE 7-05
  - Los Angeles, CA
  - Design S_a = 1.4g, MCE S_a = 2.1g





Kammula, V., Erochko, J., Kwon, O., and Christopoulos, C. (2013). "Application of hybrid-simulation to fragility assessment of the telescoping self-centering energy dissipative bracing system." *Earthquake Engineering & Structural Dynamics*.

Introduction – Hybrid Simulation

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Hybrid Simulation Frameworks

- **UI-SimCor** University of Illinois at Urbana Champaign
- **OpenSees-OpenFresco** University of California, Berkeley
- **Mercury** University of Colorado, Boulder
- **HybridFEM** Lehigh University
- **NCREE-ISEEdb** National Center for Research on Earthquake Engineering, Taiwan

- Other case-by-case implementations: Matlab Simulink, etc.

Hybrid Simulation Frameworks

- **Hybrid simulation method is a basically substructuring technique.**

$$\boldsymbol{m}\ddot{\boldsymbol{u}} + \boldsymbol{c}\dot{\boldsymbol{u}} + \boldsymbol{r}(\boldsymbol{u}, \dot{\boldsymbol{u}}, \ddot{\boldsymbol{u}}) = \boldsymbol{f}(t)$$

Hybrid Simulation Frameworks

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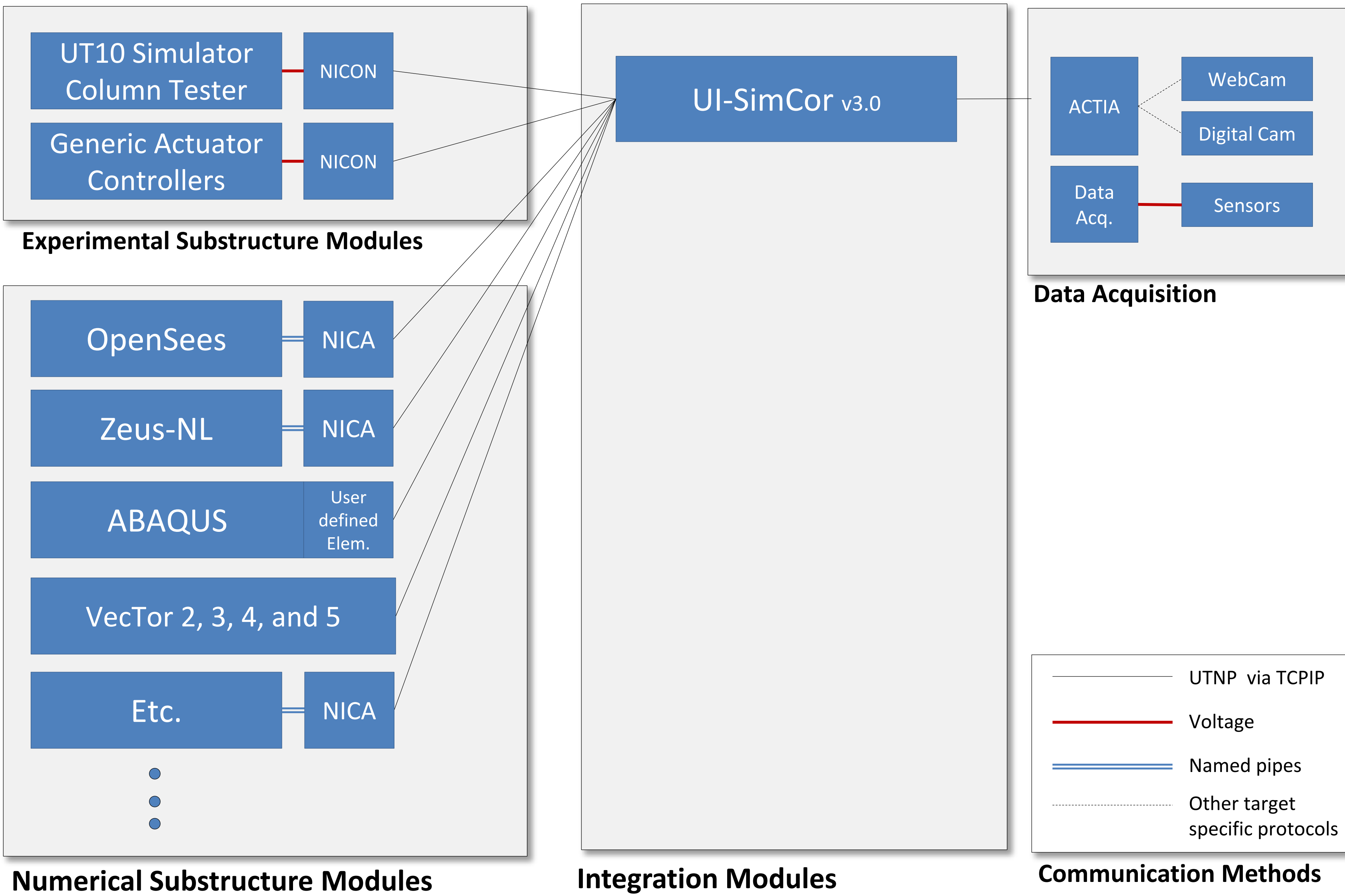
$$\boldsymbol{m}\ddot{\boldsymbol{u}} + \boldsymbol{c}\dot{\boldsymbol{u}} + \boldsymbol{r}(\boldsymbol{u}, \dot{\boldsymbol{u}}, \ddot{\boldsymbol{u}}) = \boldsymbol{f}(t)$$

- **General requirements in hybrid simulations**
  - Main numerical integration module
    - Numerical integration scheme
    - None-iterative method for real-time hybrid simulation
  - Communication between substructure modules and the integration module
  - Capability to impose predicted displacements to an actuator controller
  - Actuator delay compensation in real-time hybrid simulation

UT-SIM: University of Toronto Simulation Framework



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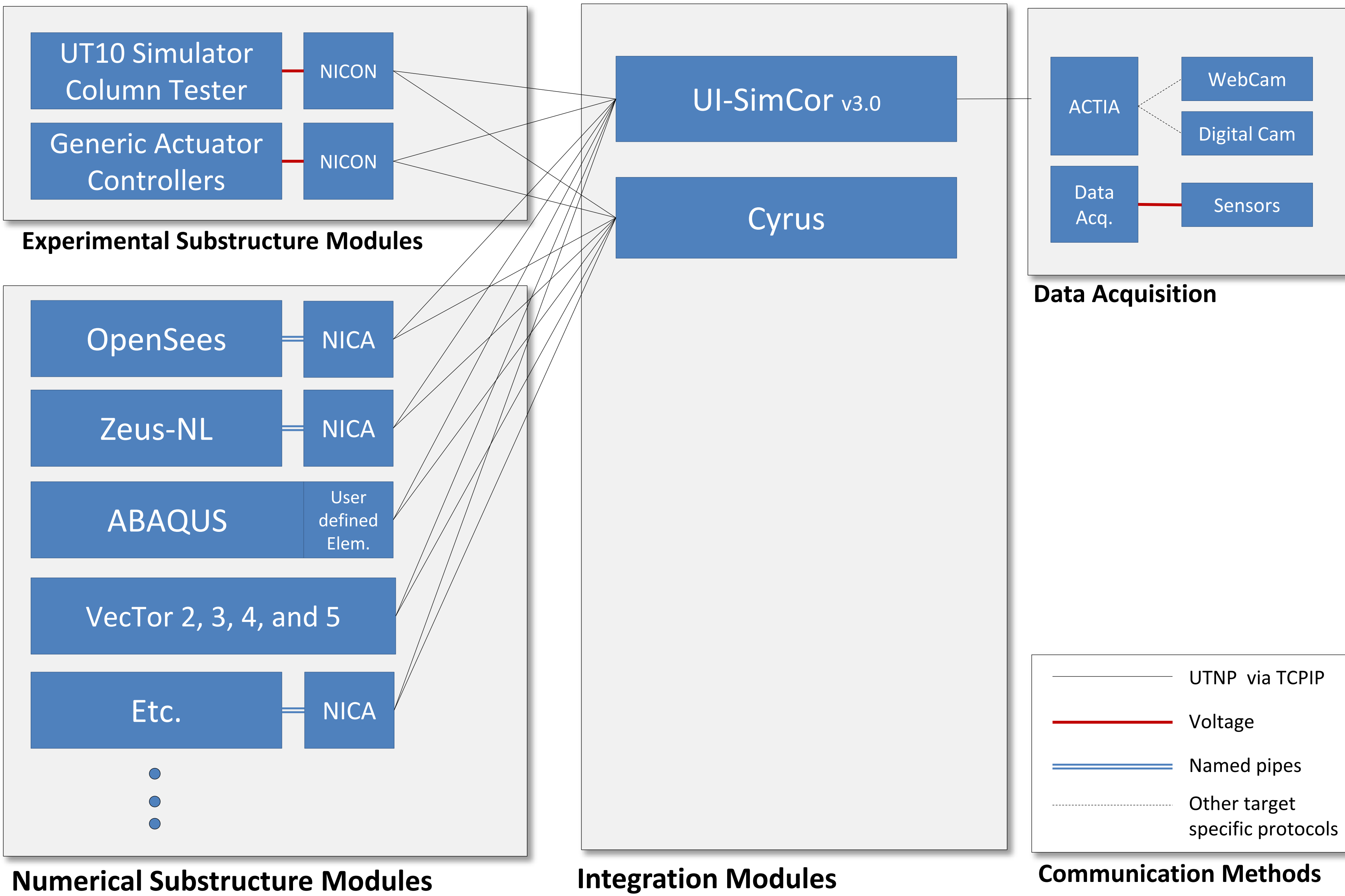

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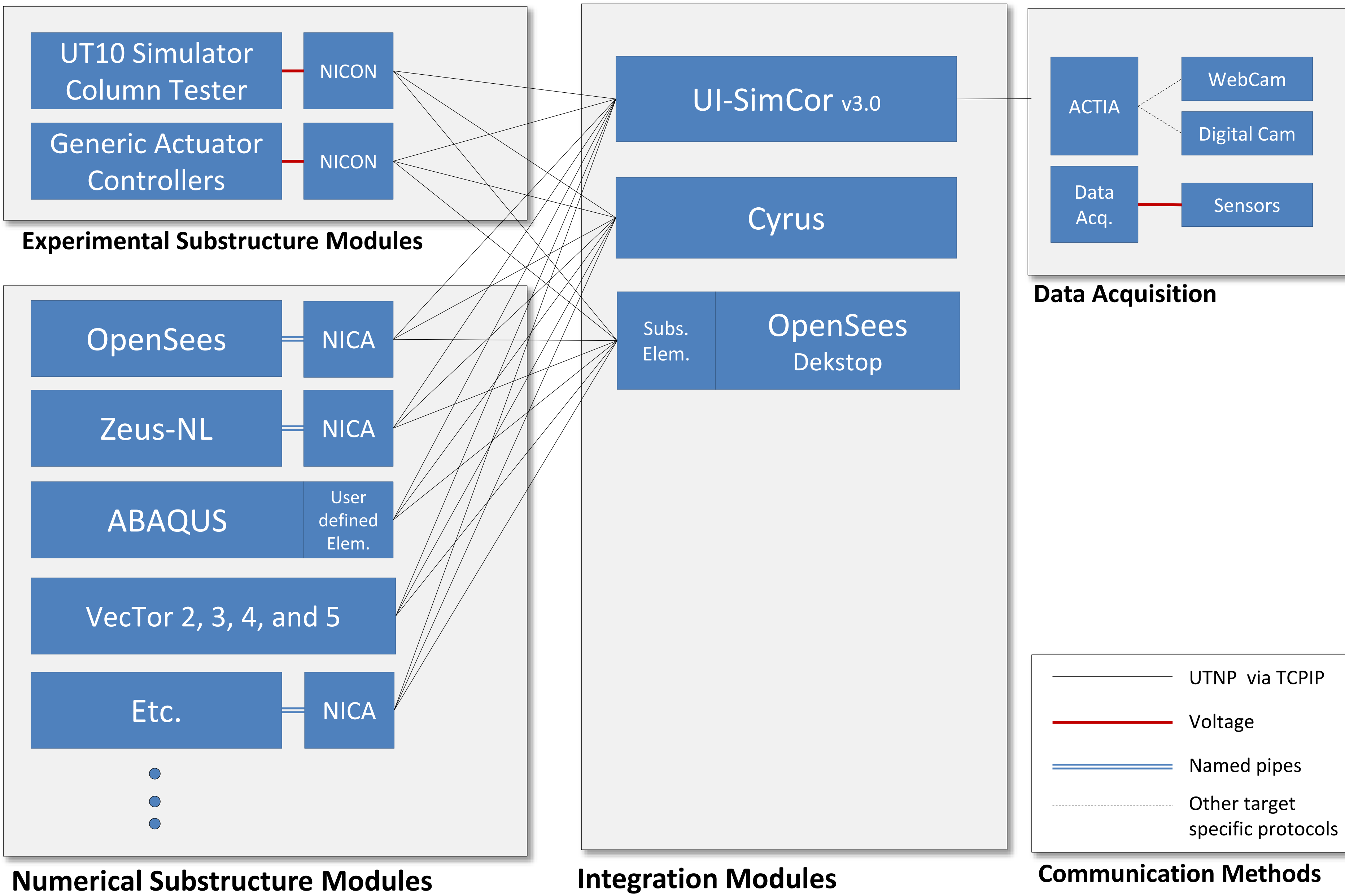

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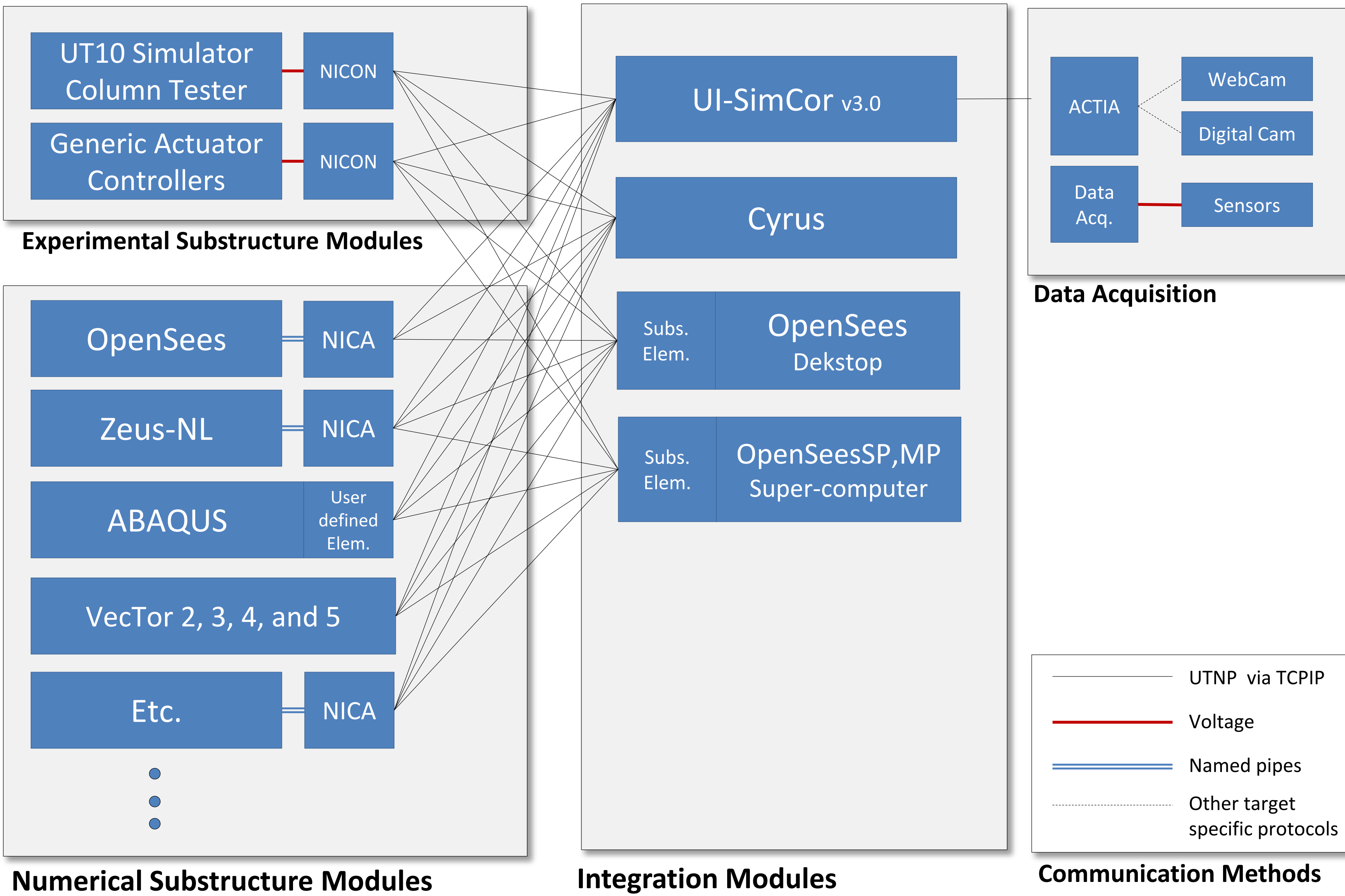

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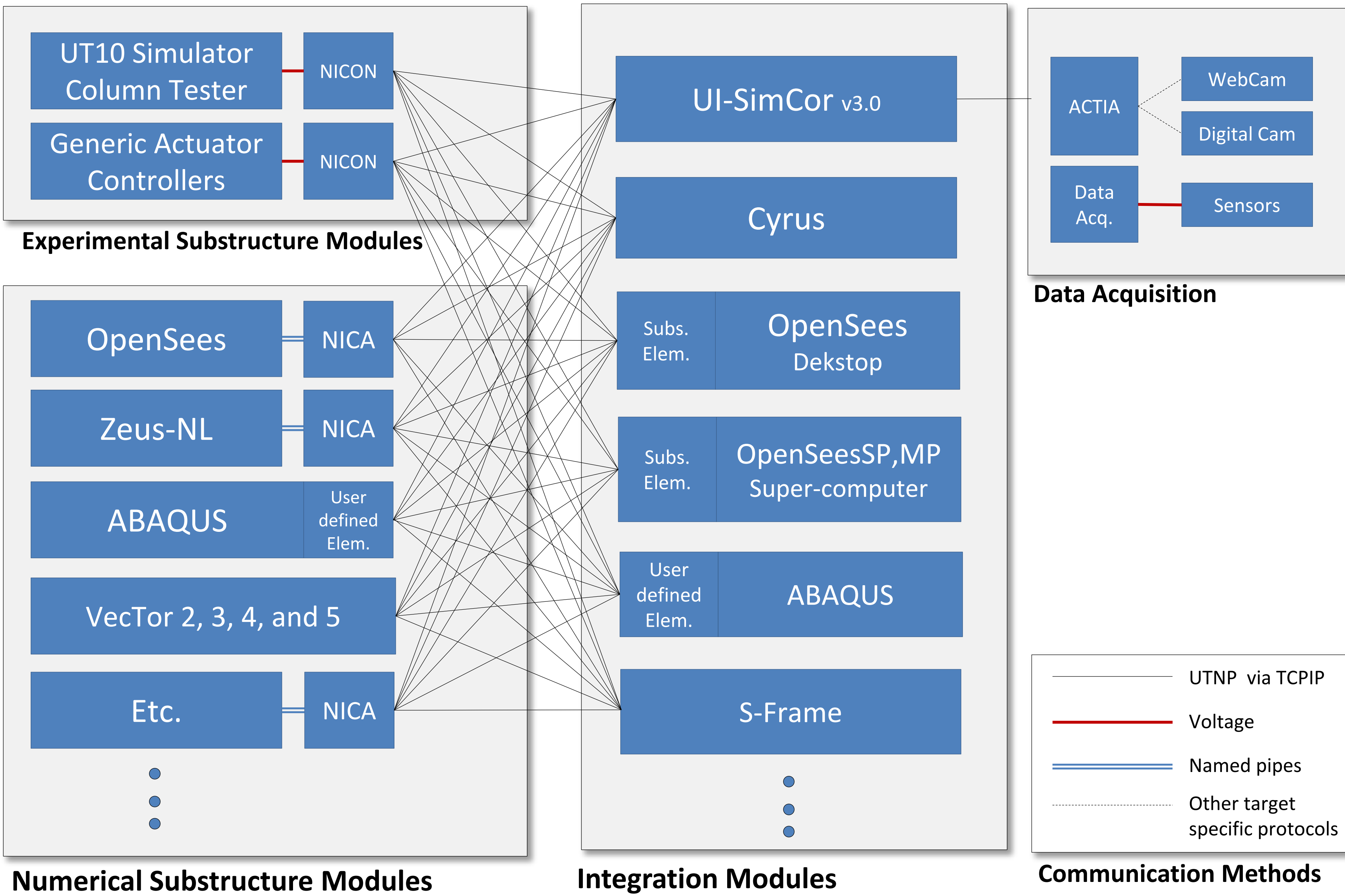

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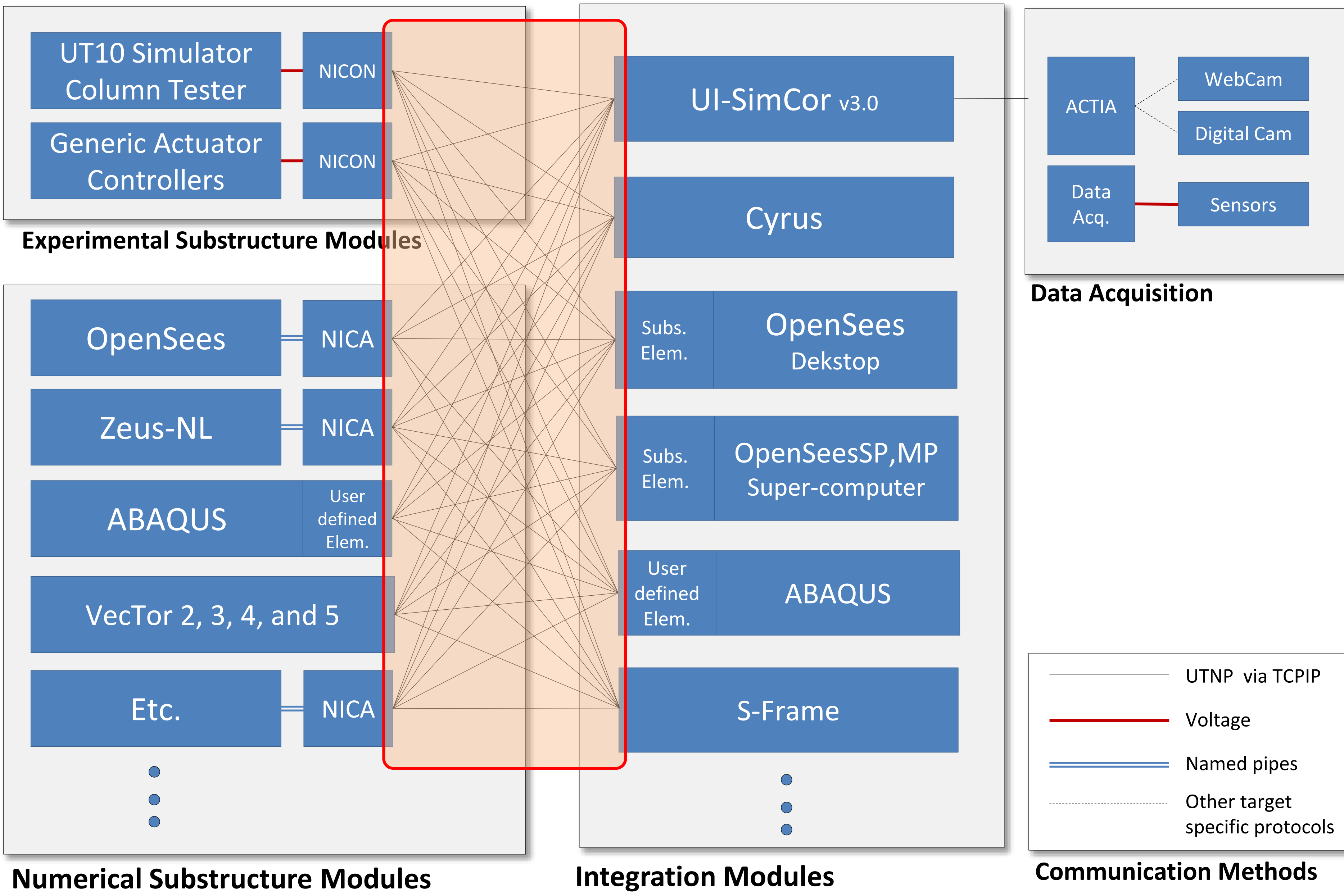

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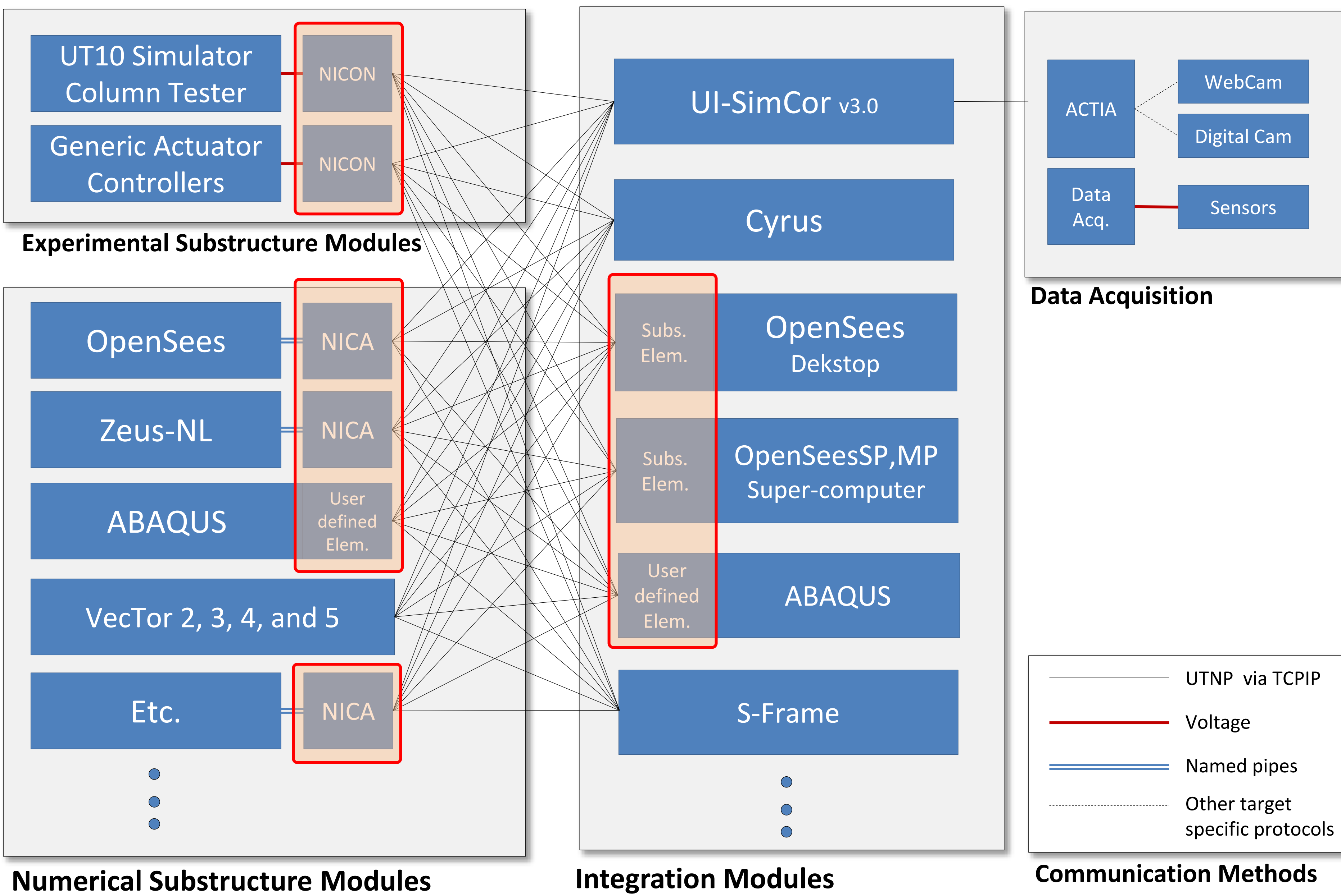


UT-SIM: University of Toronto Simulation Framework

- **Standardized data exchange format and communication protocol**
  - Structure of data to be transmitted between an integration module and substructure modules
  - Cover parameters and indicators that are needed for various simulation purposes (e.g. hybrid thermal simulation, real-time simulation, etc.)
  - Have flexibility for future extension

32 bit

Version	Command	Test type	Substructure type
Precision	Data type	Number of DOFs	
Step number		Reserved for future extension	
Time stamp			
Data			

16 bytes

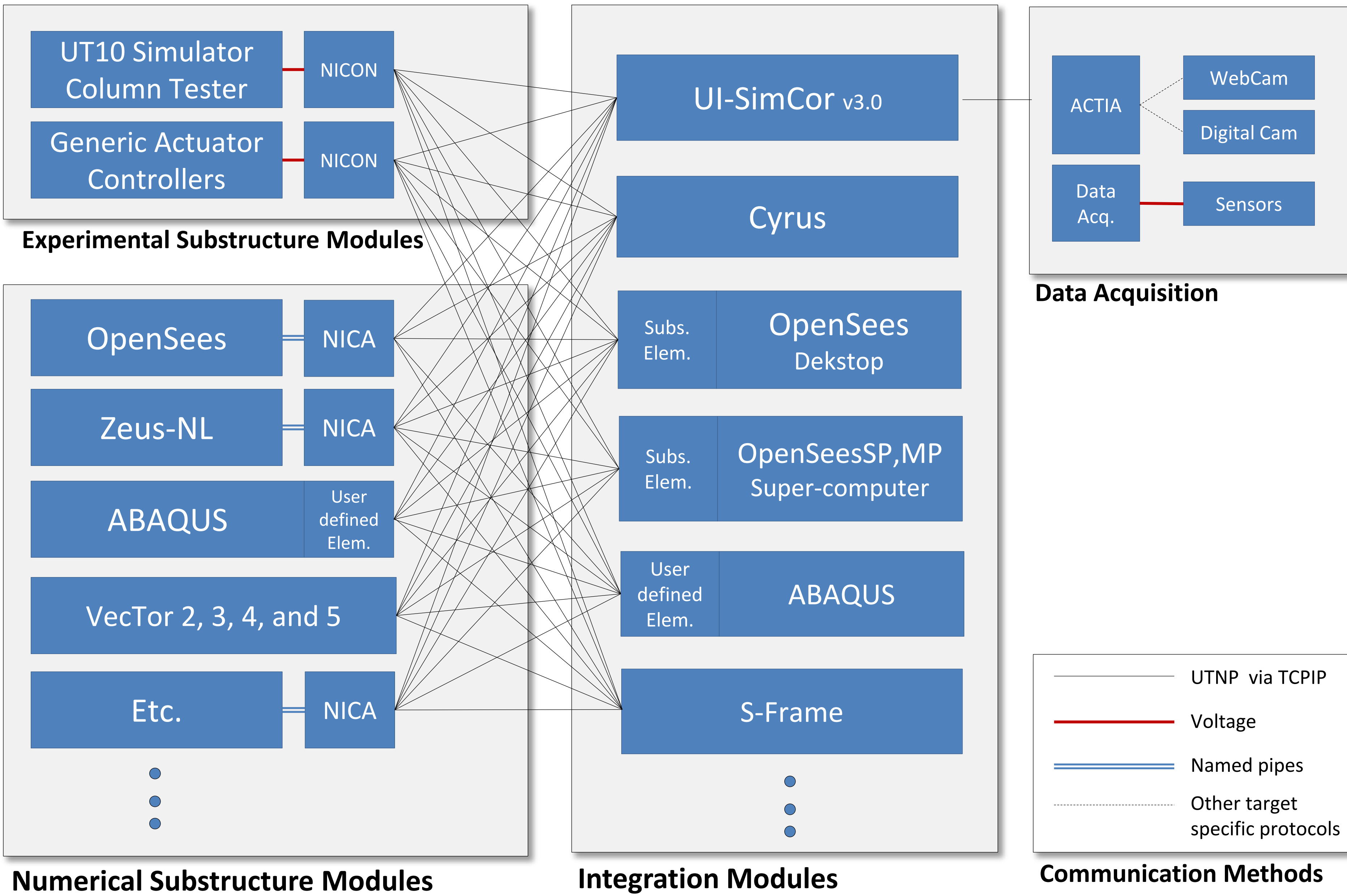
Size depends on header

UT-SIM: University of Toronto Simulation Framework

- **Encapsulate data exchange format and communication related functions**
  - Shared library or shared object file (***DataExchange.dll*** or ***DataExchange.out***)
  - Compile all functions as a DLL or Object, and then use the same code in all applications
  - Designed in such a way that it is compatible with different languages.
    - C++ (OpenSees, NICA)
    - Fortran (VecTor programs, Abaqus, ANSYS)
    - LabVIEW (NICON)
    - MATLAB (UI-SimCor)

Huang X, Kwon OS. Development of integrated framework for distributed multi-platform simulation. 6AESE/11ANCRiSST, Champaign, IL: 2015.

UT-SIM: University of Toronto Simulation Framework



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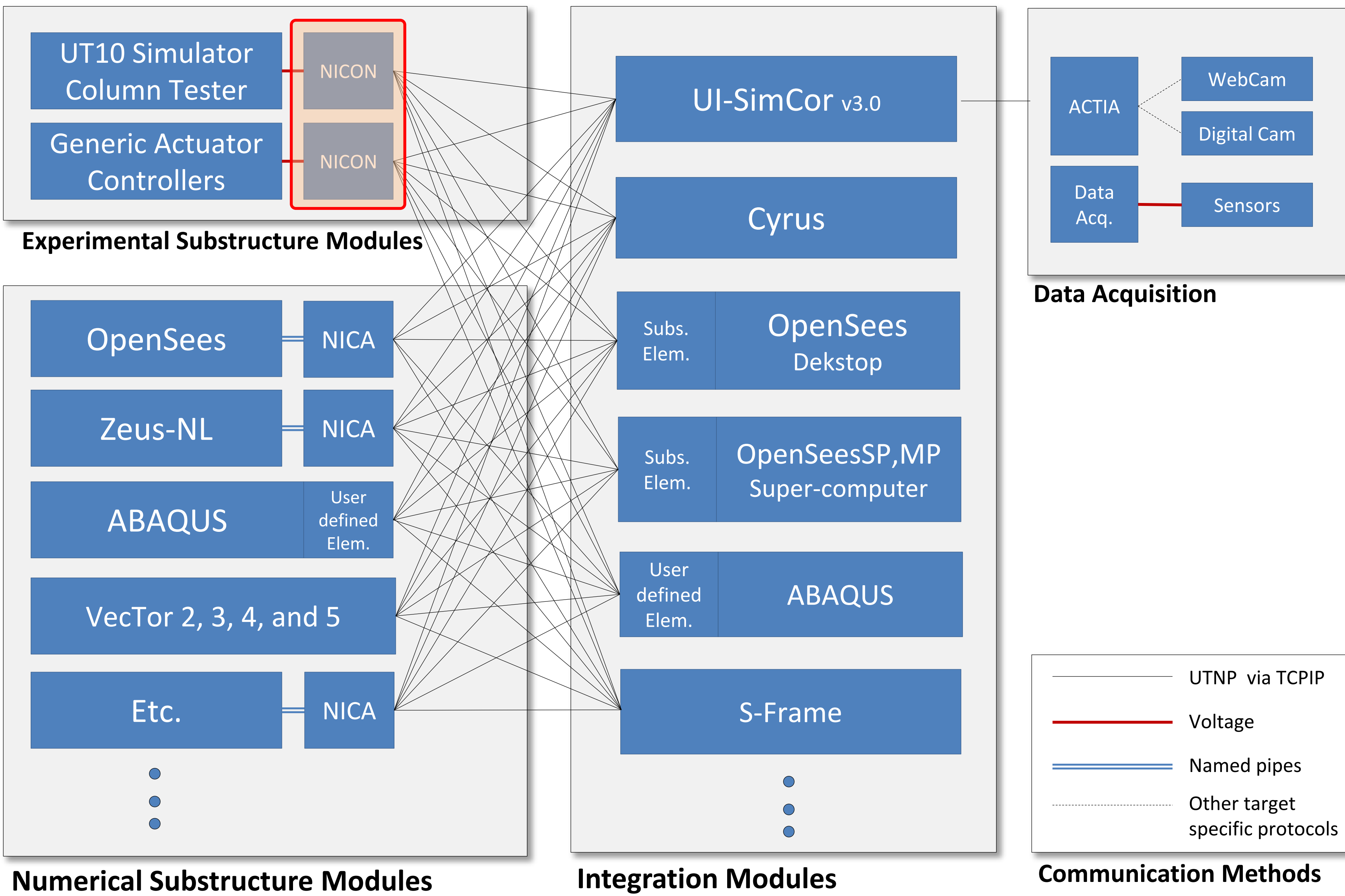
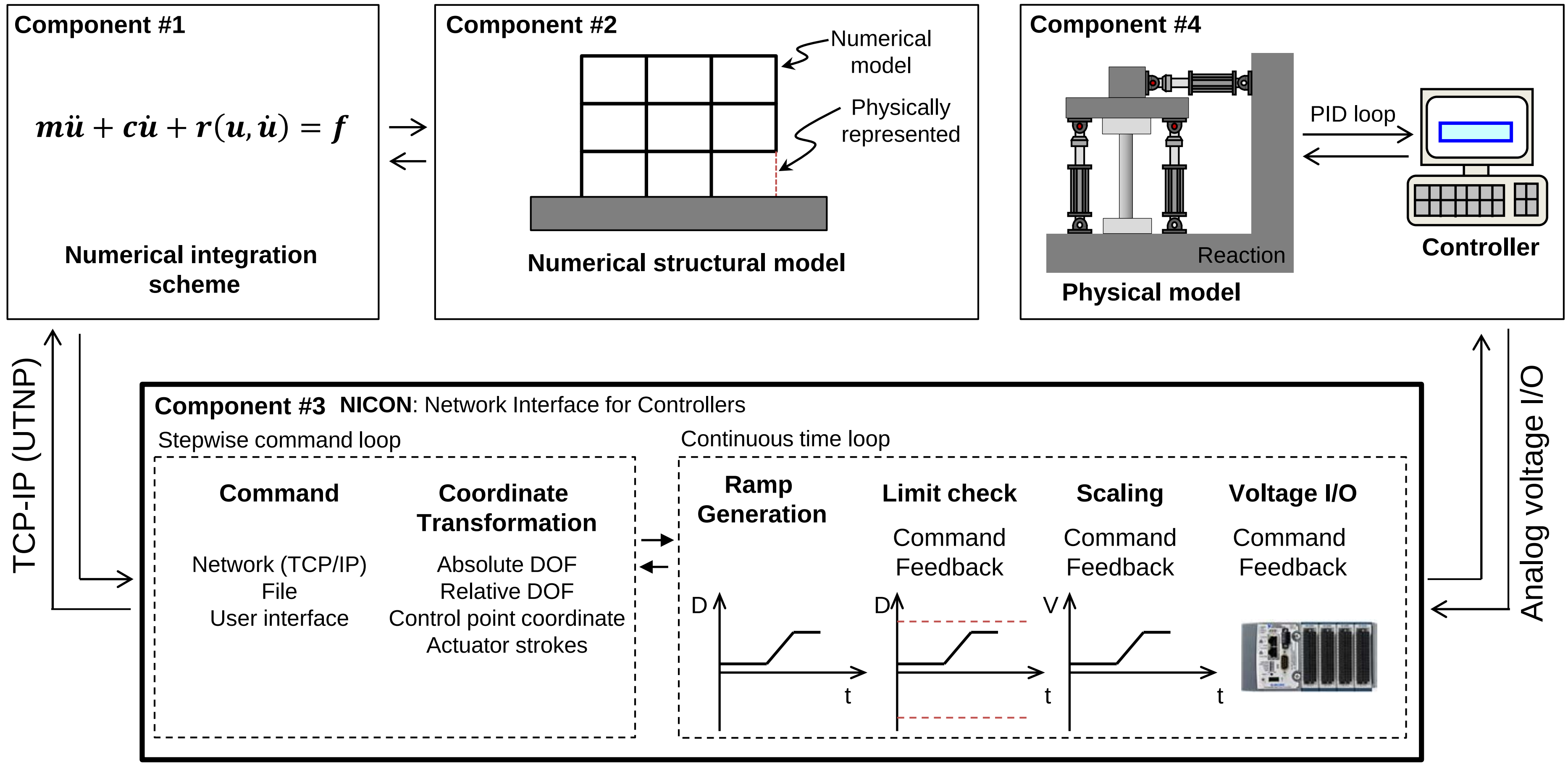


NICON – Network Interface for Controllers

❑ Required Functionalities - Communication



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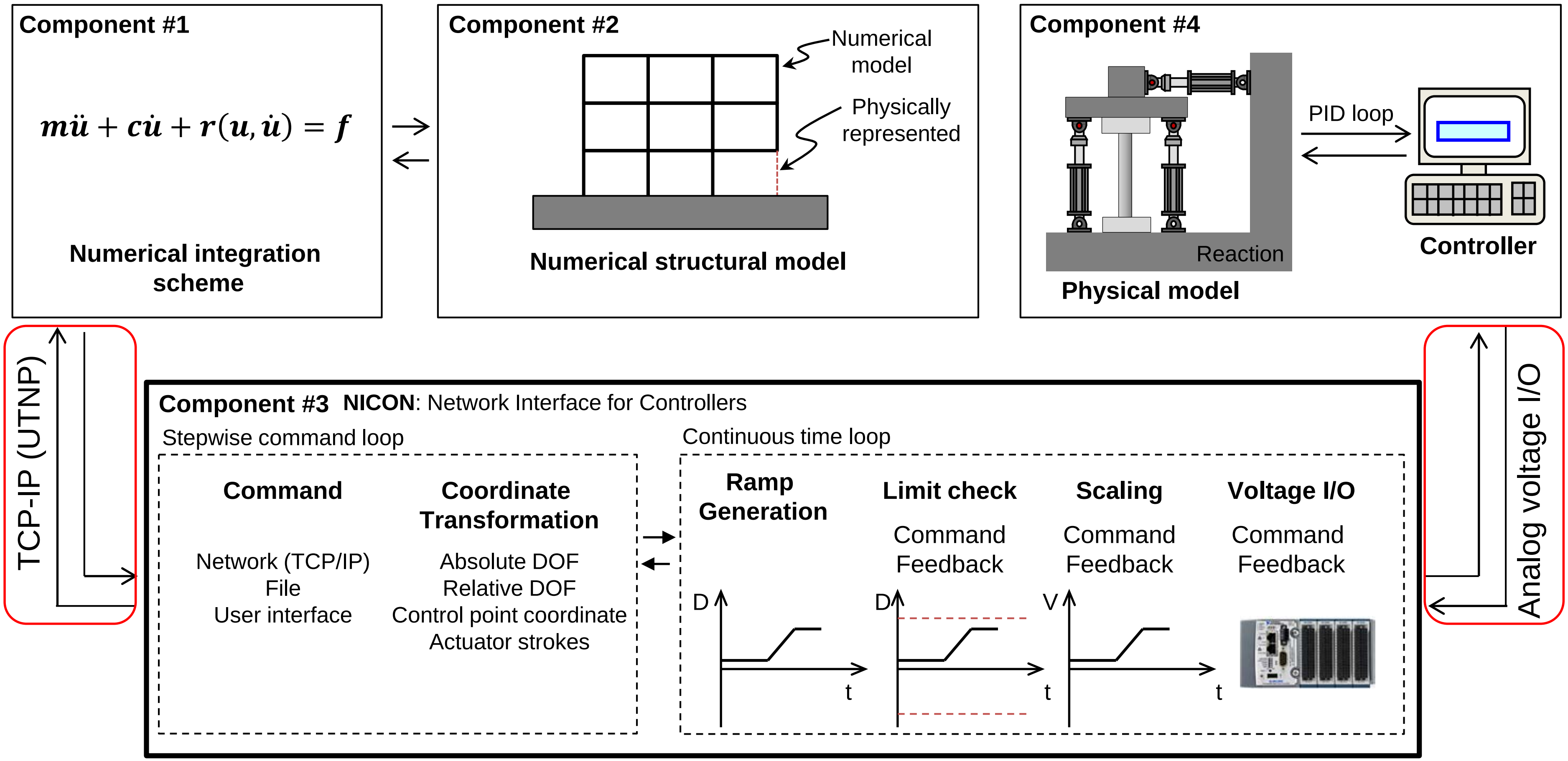

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NICON – Network Interface for Controllers

Required Functionalities - Communication

- Methods for communication with actuator controllers
  - Shared memory approach: SCRAMNet
  - Analog voltage input/output method
- Analog voltage input/output with actuator controllers
  - MTS FlexTest, Shore Western, Instron

NICON

Software written with LabVIEW	**Hardware** from National Instrument (cRIO, USBDaq, etc)

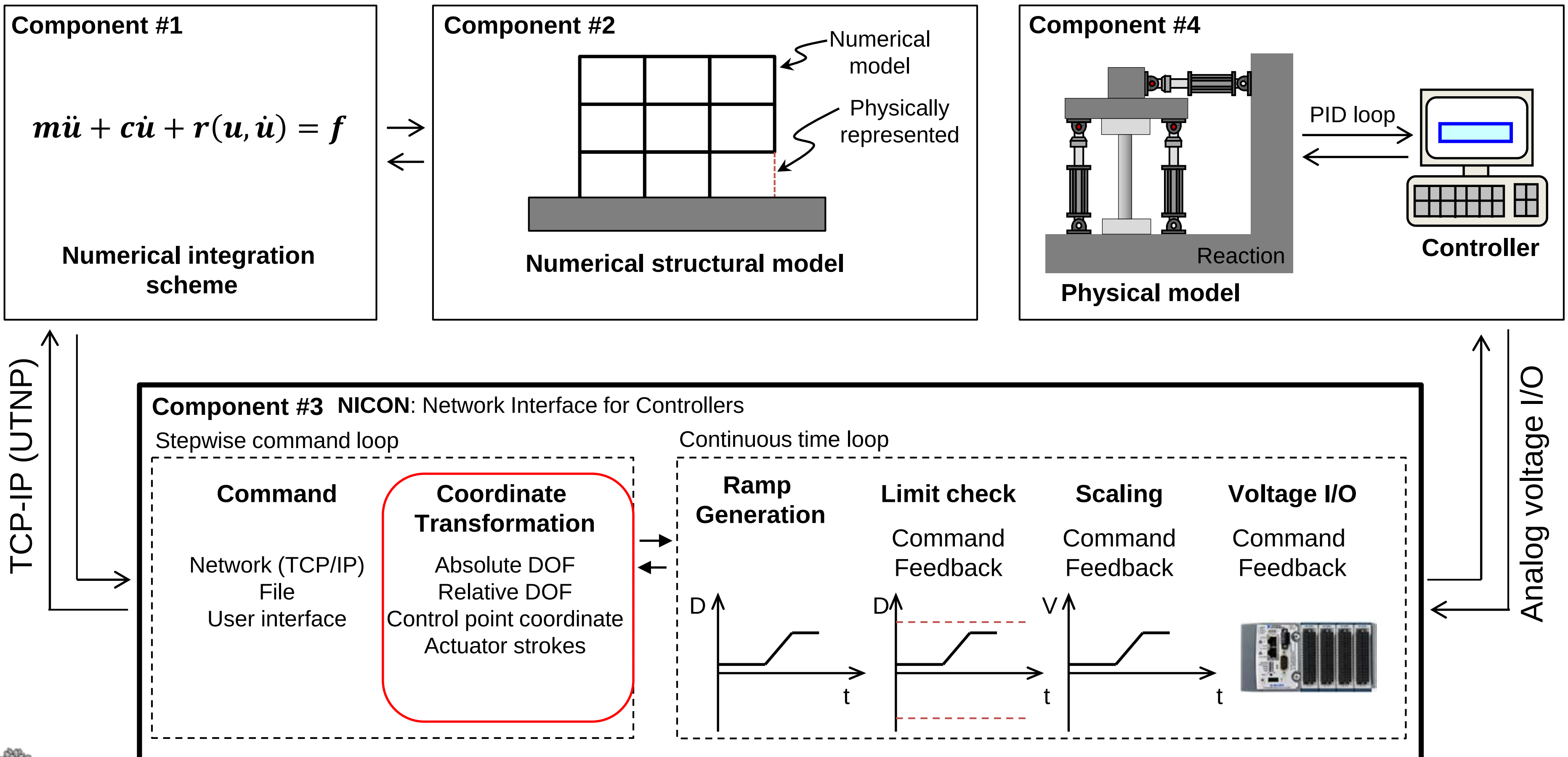
TCP-IP

Voltage I/O

Actuator Controllers

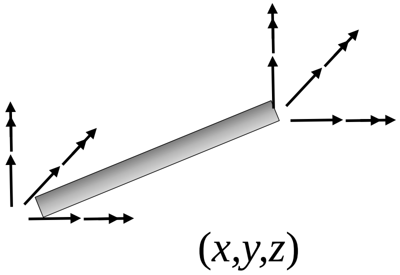
NICON – Network Interface for Controllers

❑ Required Functionalities – Coordinate transformation



NICON – Network Interface for Controllers

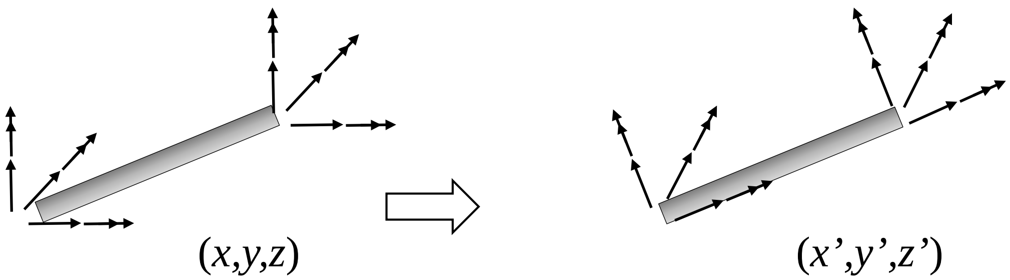
- **Required Functionalities – Coordinate transformation**



(a) Total displacements in the global coordinate

NICON – Network Interface for Controllers

❑ Required Functionalities – Coordinate transformation

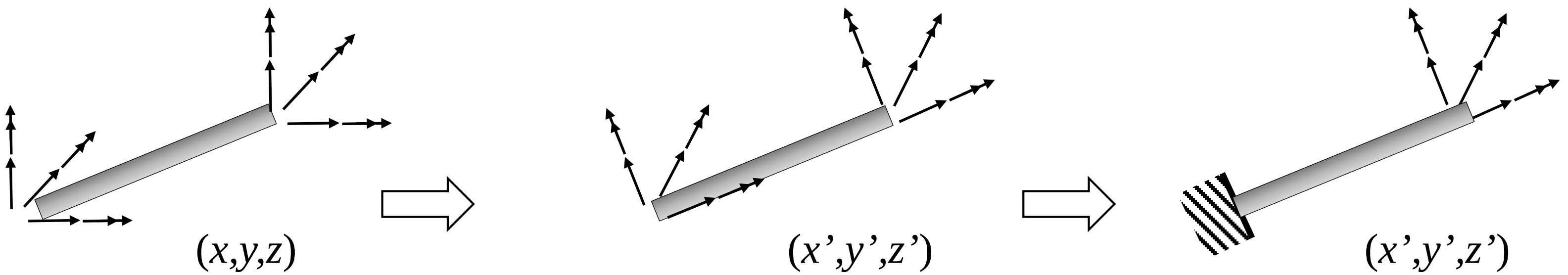


(a) Total displacements in the global coordinate

(b) Total displacements in the element coordinate

NICON – Network Interface for Controllers

❑ Required Functionalities – Coordinate transformation



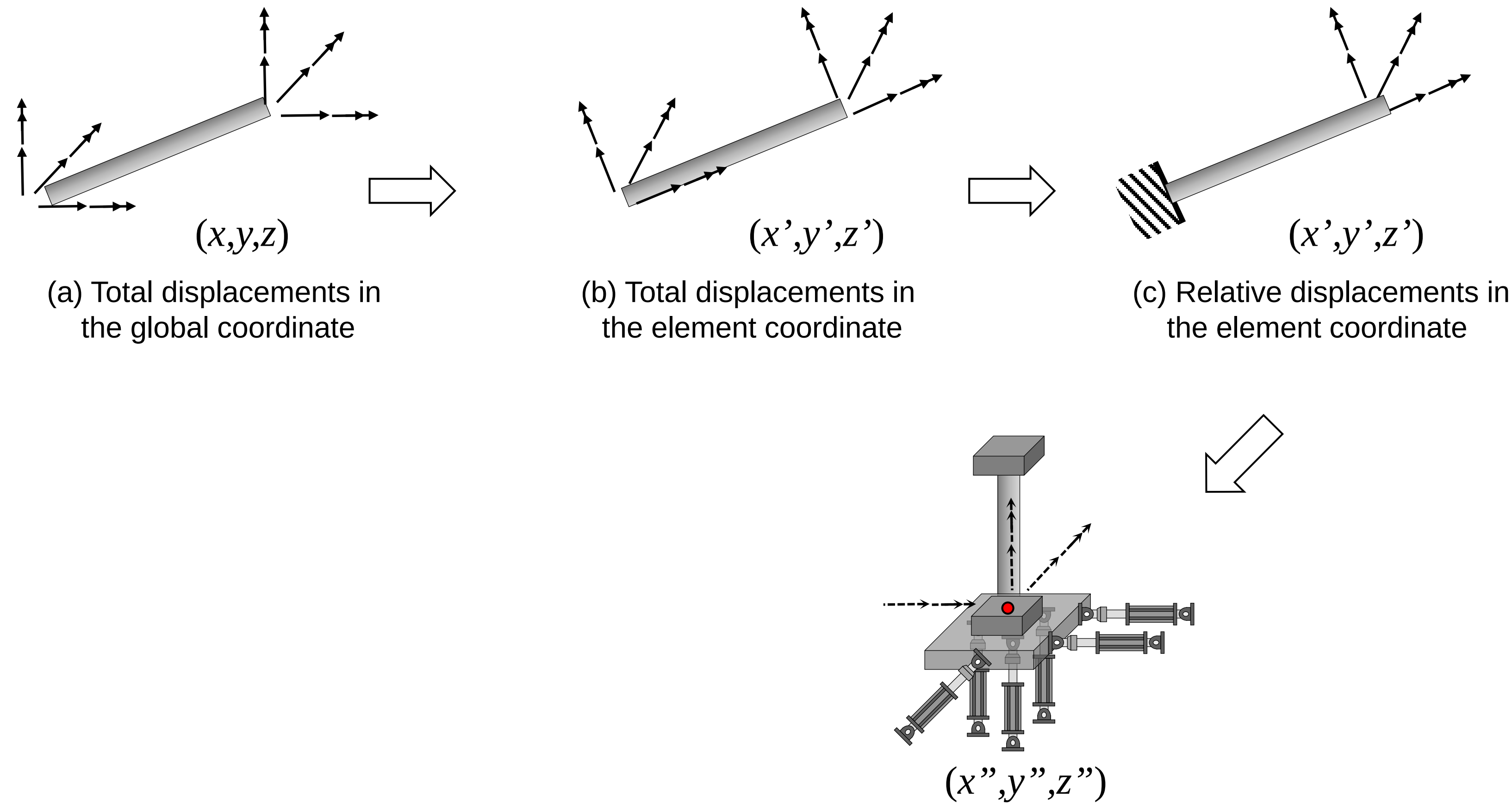
(a) Total displacements in the global coordinate

(b) Total displacements in the element coordinate

(c) Relative displacements in the element coordinate

NICON – Network Interface for Controllers

❑ Required Functionalities – Coordinate transformation



(a) Total displacements in the global coordinate

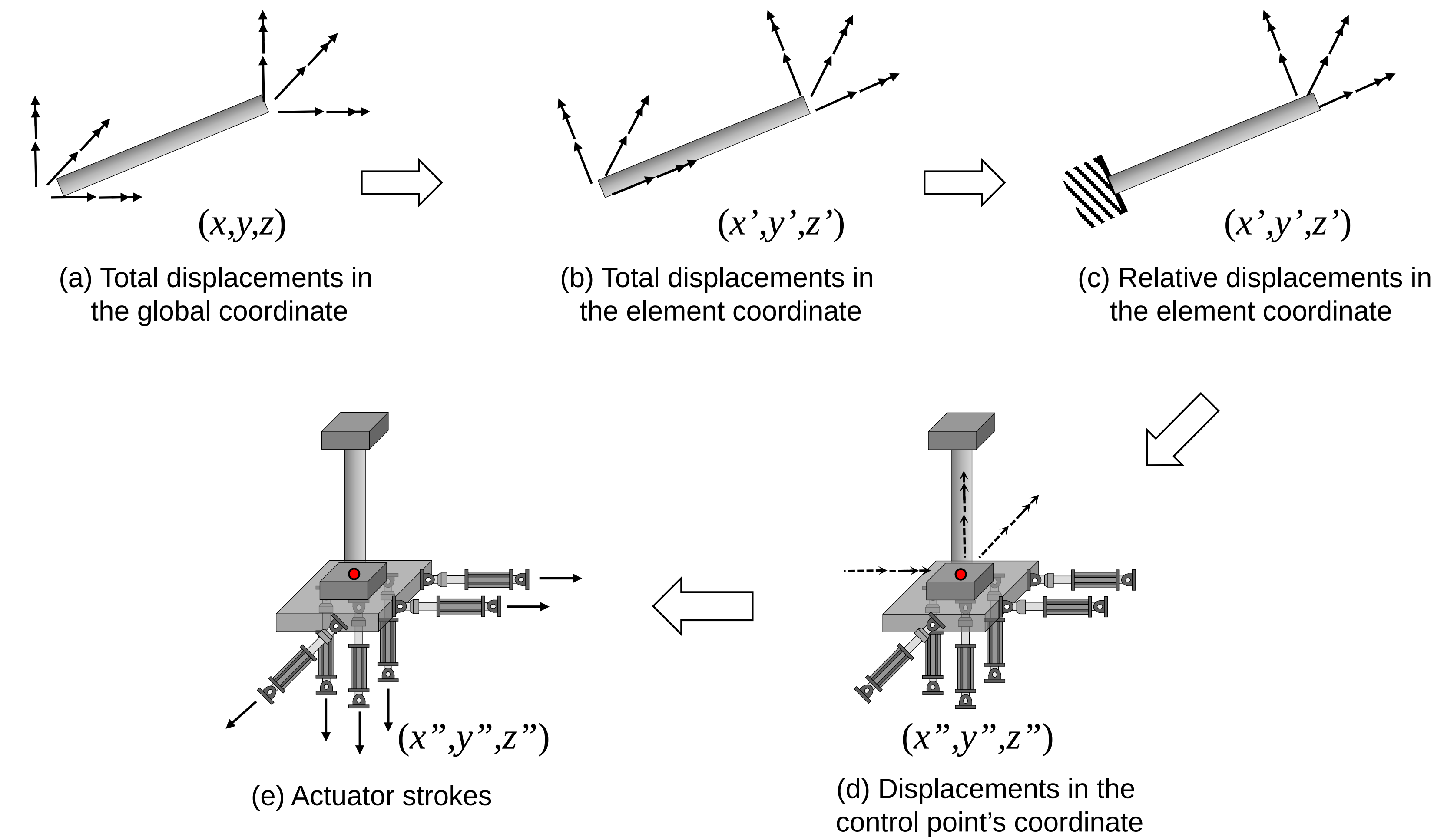
(b) Total displacements in the element coordinate

(c) Relative displacements in the element coordinate

(d) Displacements in the control point’s coordinate

NICON – Network Interface for Controllers

❑ Required Functionalities – Coordinate transformation



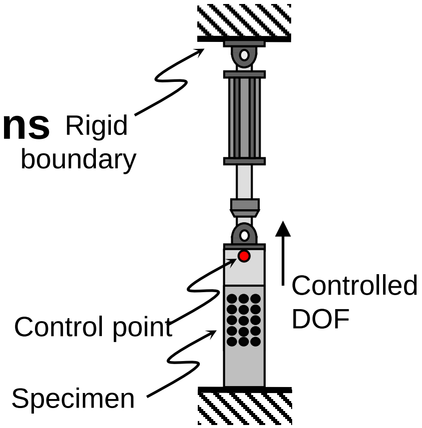
NICON – Network Interface for Controllers

- **Required Functionalities**
  – Customization for diverse experimental configuration

Applications (a) Axial elements (braces, dampers)

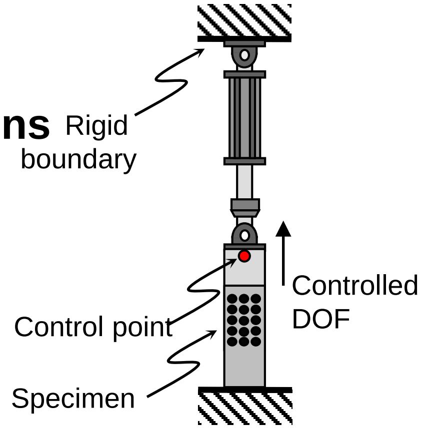
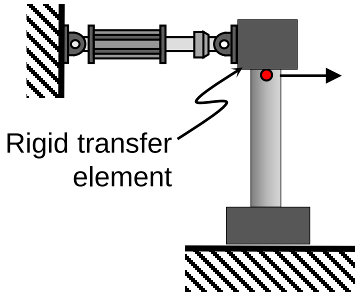
DOFs 1

Testing configurations



NICON – Network Interface for Controllers

- **Required Functionalities**
  – Customization for diverse experimental configuration

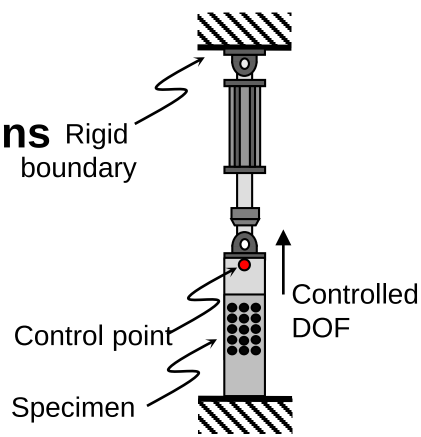
Applications	(a) Axial elements (braces, dampers)	(b) Flexural elements
DOFs	1	1
Testing configurations		

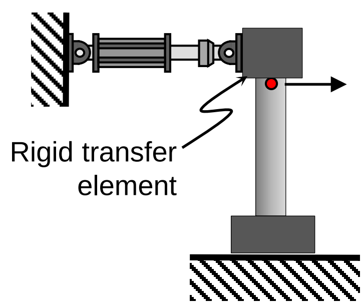
NICON – Network Interface for Controllers

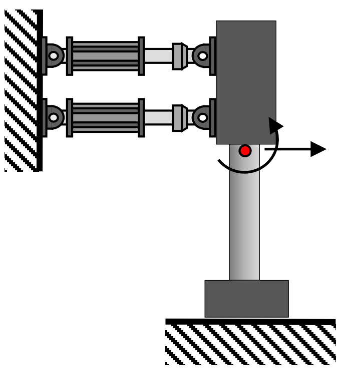
❑ Required Functionalities
– Customization for diverse experimental configuration

Applications	(a) Axial elements (braces, dampers)	(b) Flexural elements	(c) Flexural elements
DOFs	1	1	2

Testing configurations





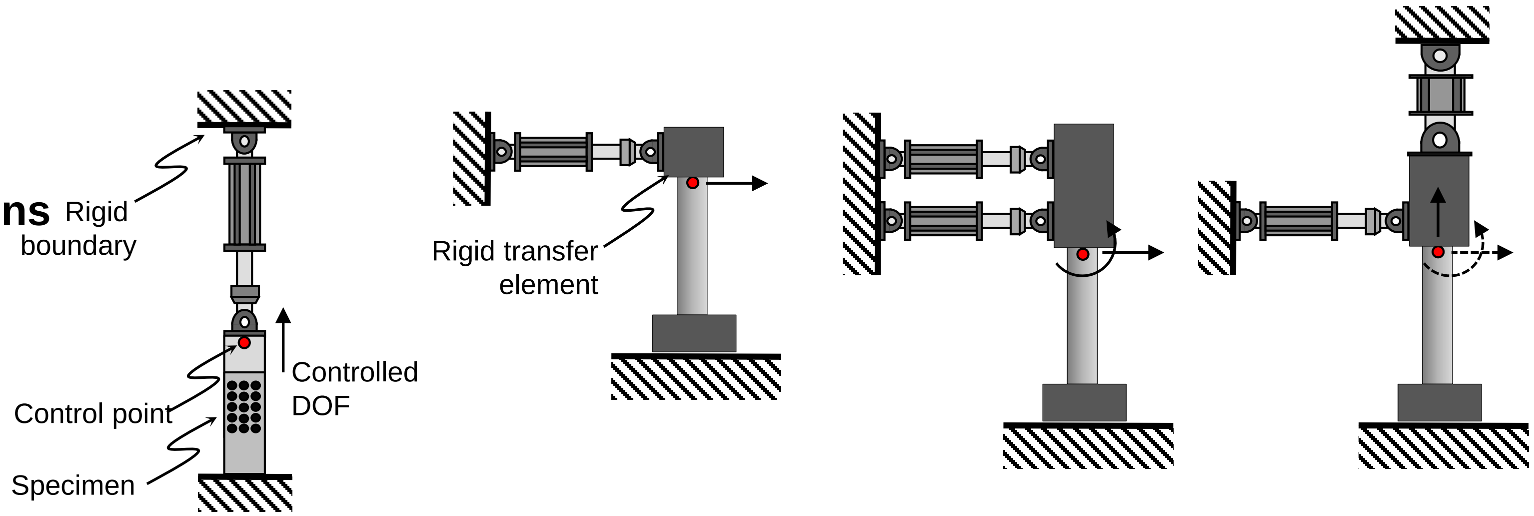


NICON – Network Interface for Controllers

❑ Required Functionalities
– Customization for diverse experimental configuration

Applications	(a) Axial elements (braces, dampers)	(b) Flexural elements	(c) Flexural elements	(d) Beam-column elements
DOFs	1	1	2	2

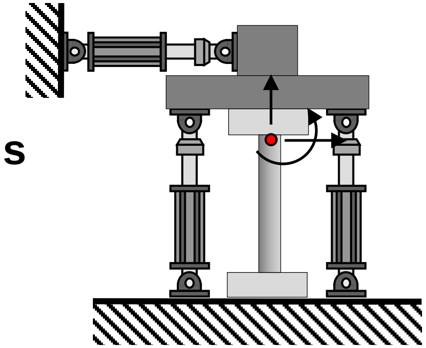
Testing configurations



NICON – Network Interface for Controllers

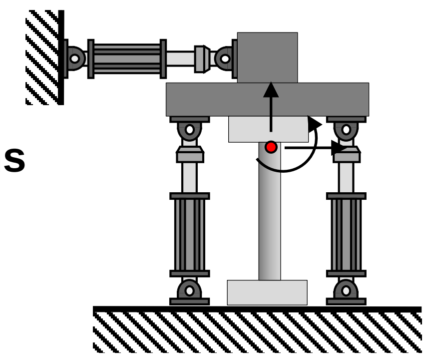
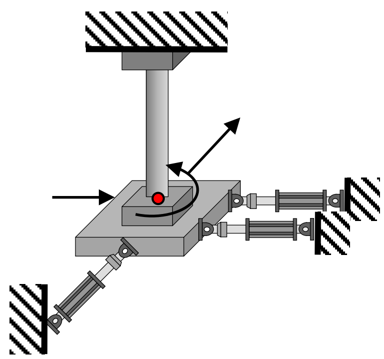
❑ Required Functionalities

– Customization for diverse experimental configuration

Applications	(e) Beam-column elements
DOFs	3
Testing configurations	

NICON – Network Interface for Controllers

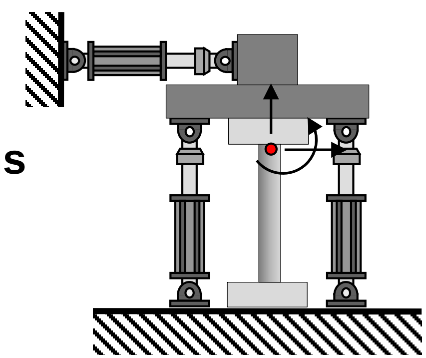
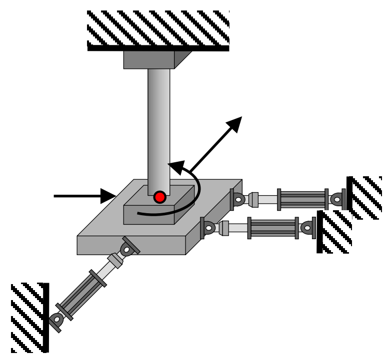
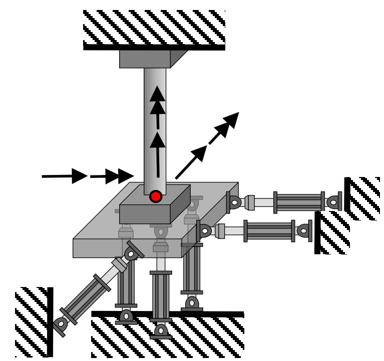
- **Required Functionalities**
  - **– Customization for diverse experimental configuration**

Applications	(e) Beam-column elements	(f) Flexural-torsional elements
DOFs	3	3
Testing configurations		

NICON – Network Interface for Controllers

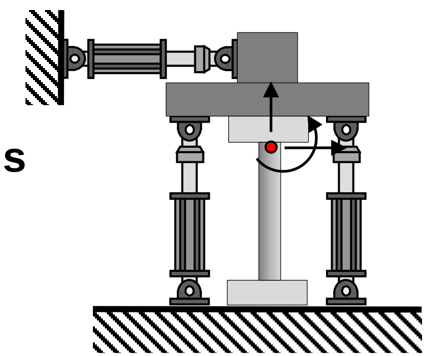
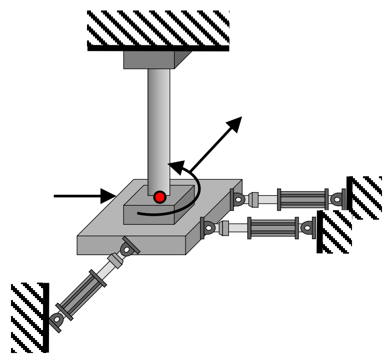
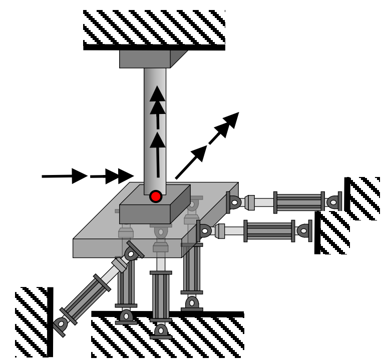
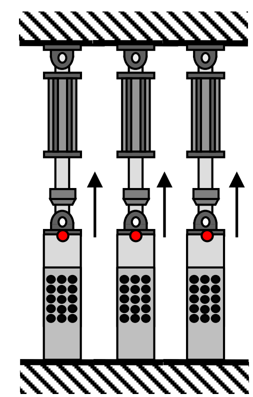
❑ Required Functionalities

– Customization for diverse experimental configuration

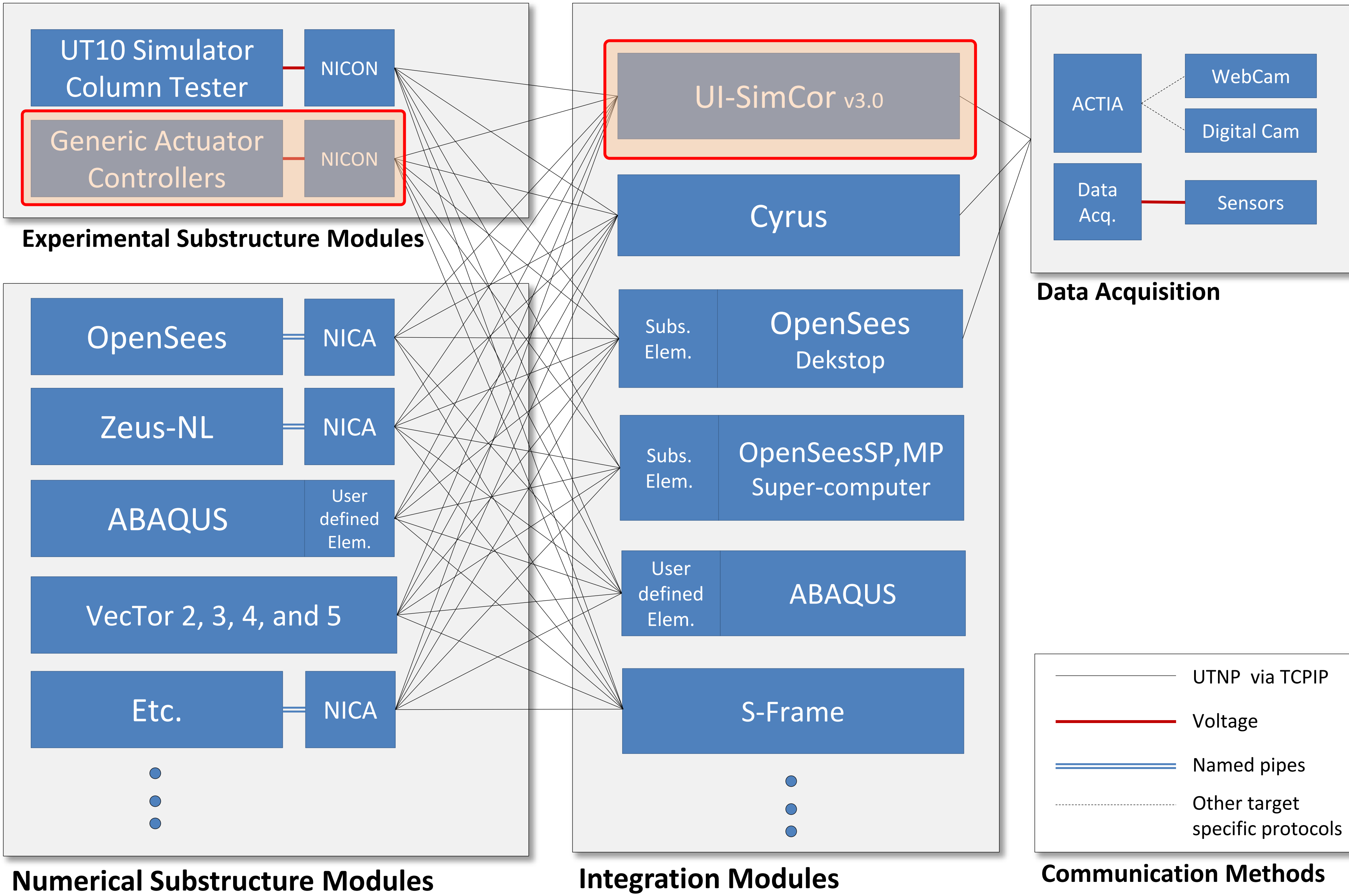
Applications	(e) Beam-column elements	(f) Flexural-torsional elements	(g) General 6DOF frame elements
DOFs	3	3	6
Testing configurations			

NICON – Network Interface for Controllers

❑ Required Functionalities
– Customization for diverse experimental configuration

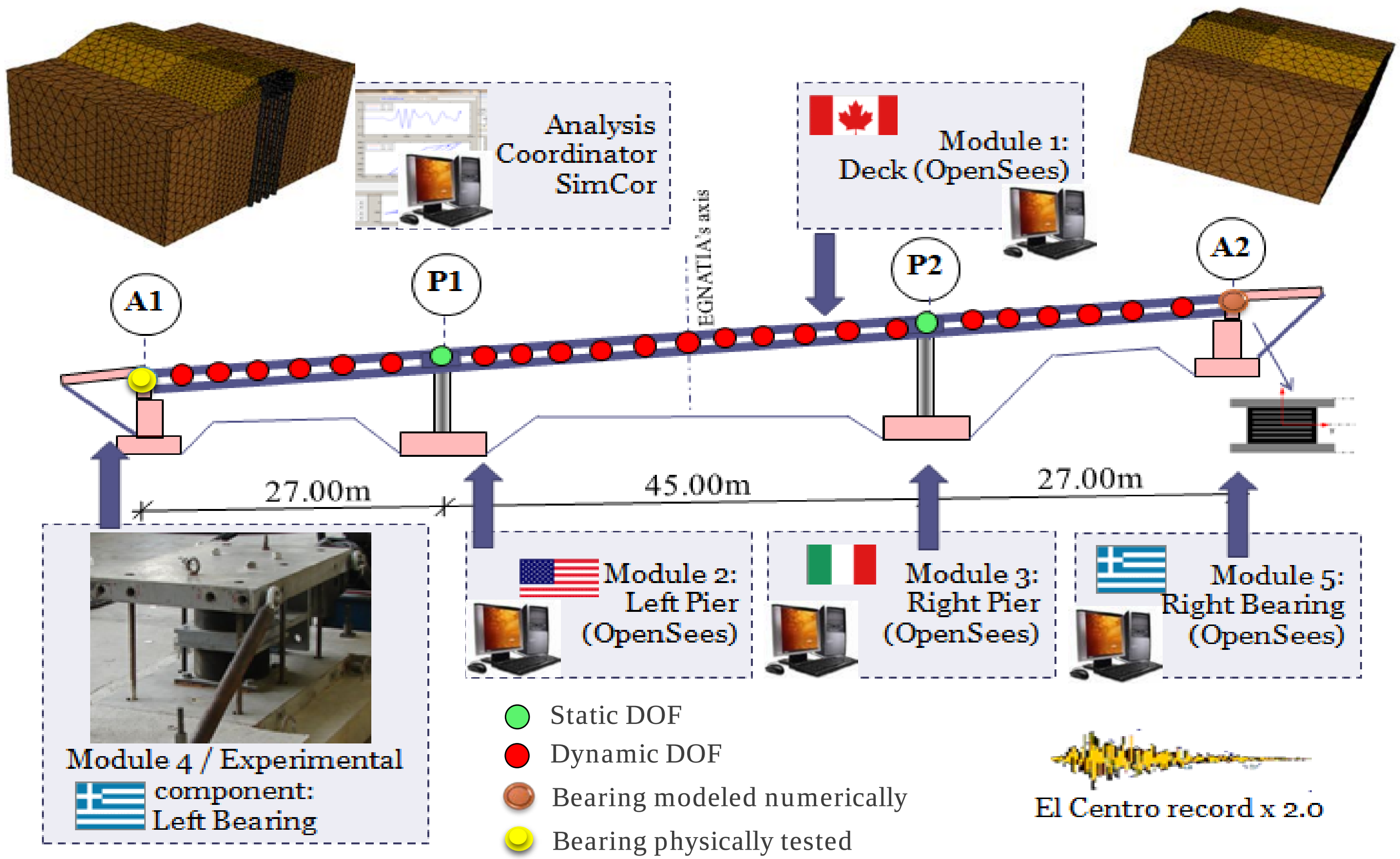
Applications	(e) Beam-column elements	(f) Flexural-torsional elements	(g) General 6DOF frame elements	(h) Multiple 1DOF elements
DOFs	3	3	6	n
Testing configurations				

UT-SIM: Application Example 1



Geographically Distributed Simulation

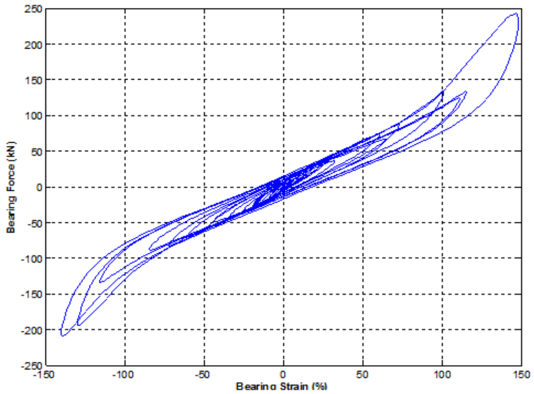
❑ Inter-continental Hybrid Simulation



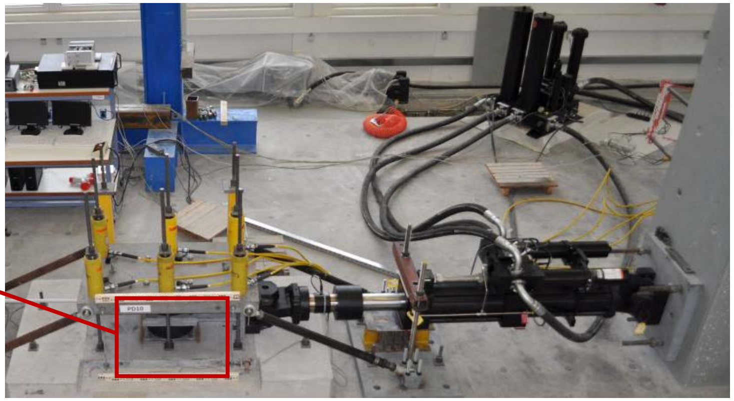
Sextos, A. G., Bousias, S., Taskari, O., Evangeliou, N., Kwon, O., Elnashai, A., Di Sarno, L., and Palios, X. (2014). "An intercontinental hybrid simulation experiment for the purposes of seismic assessment of a three-span R/C bridge." *10th National Conference on Earthquake Engineering2*, Anchorage, Alaska.

Geographically Distributed Simulation

- Inter-continental Hybrid Simulation

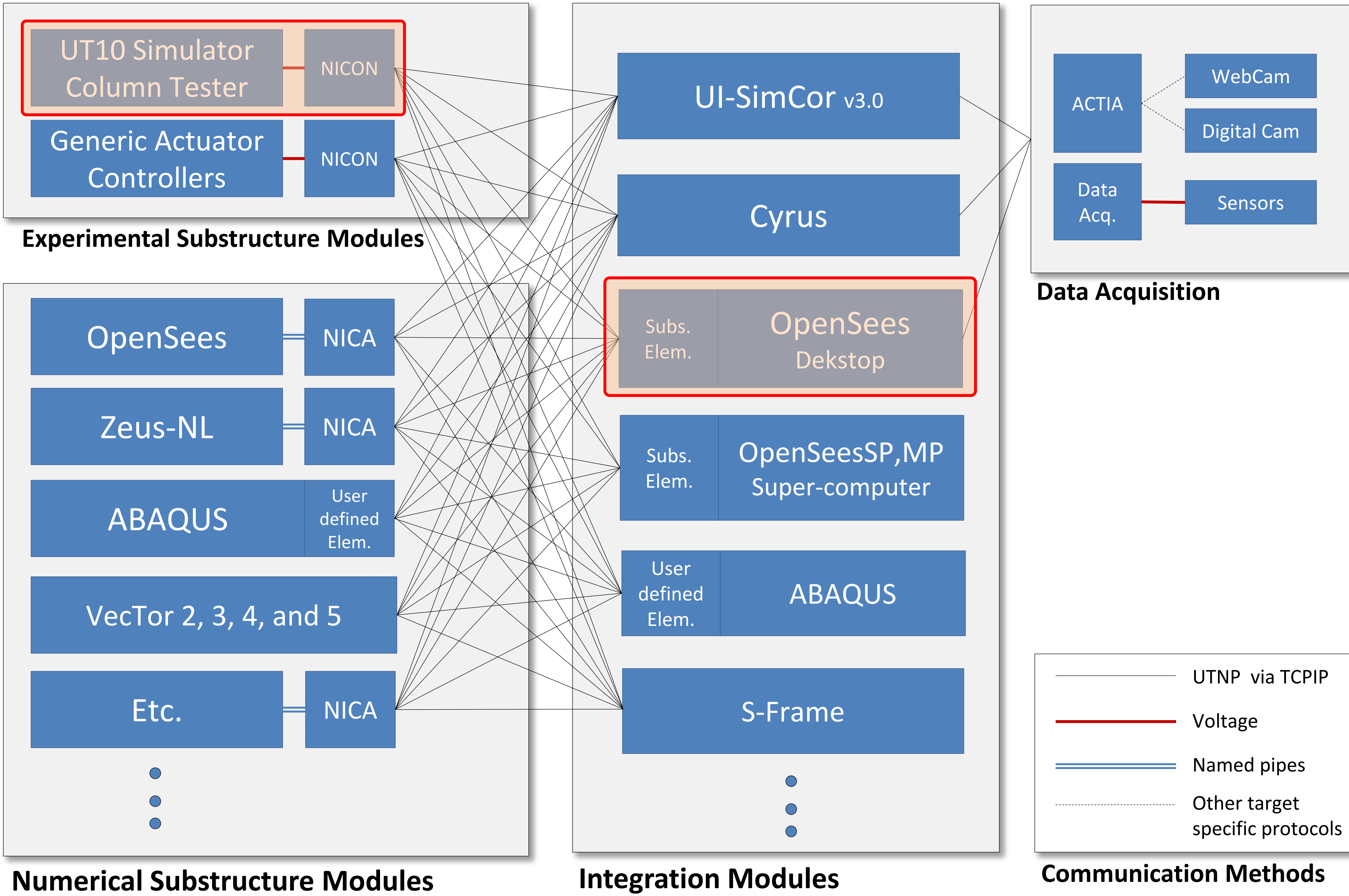


Experimental hysteretic behaviour



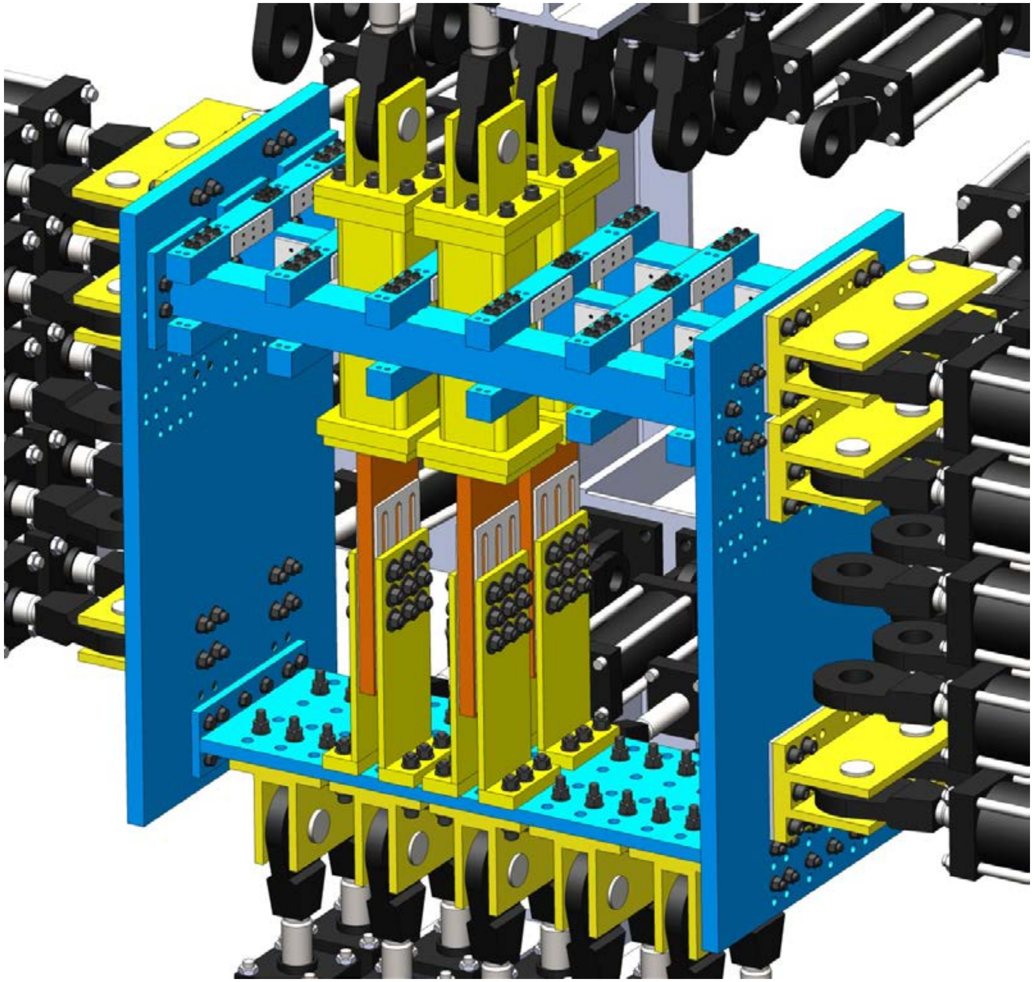
Physical specimen at University of Patras

UT-SIM: Application Example 2



UT10 Hybrid Simulator

- **Shell Element Tester**
  - 40, 1000 kN, ±150 mm in-plane actuators
  - 20, 500 kN, ±150 mm out-of-plane actuators
- **Specimen support frame**
  - Lateral stability of the system
  - Testing elements in an uncoupled mode
  - Adjustable configuration for braces with different sizes and load capacities

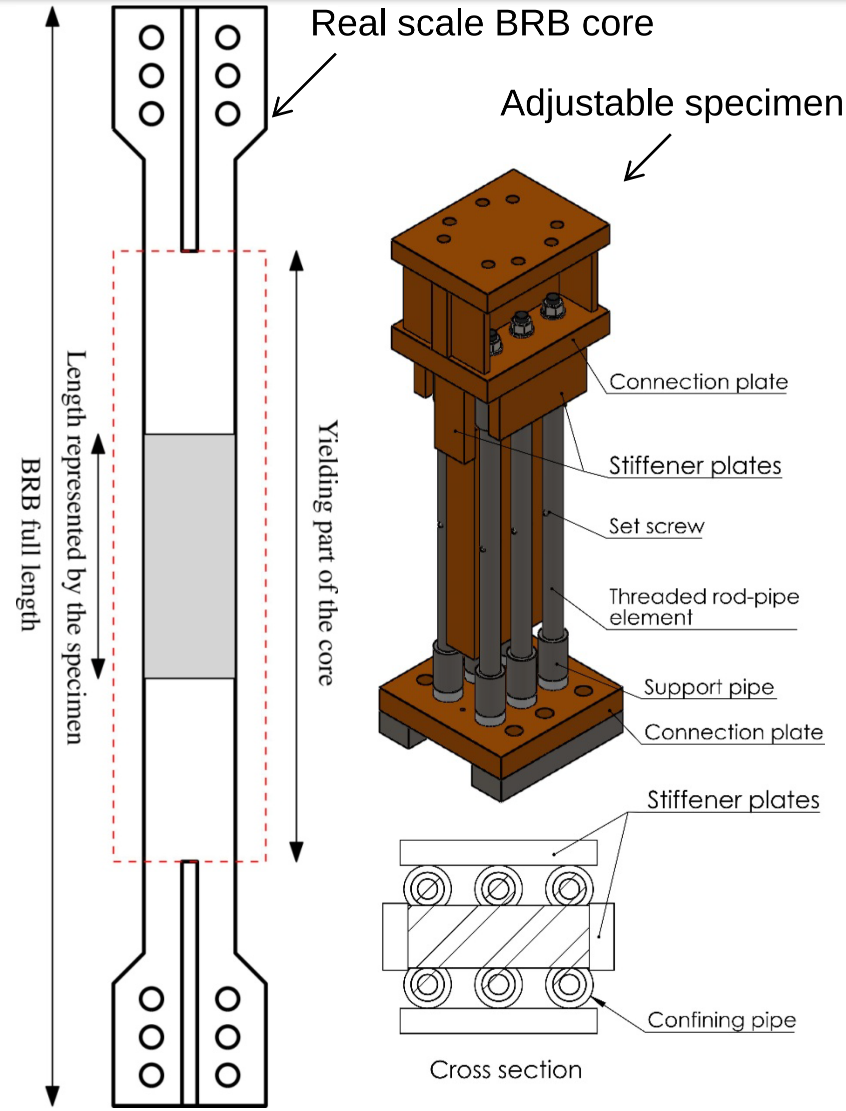


UT10 Hybrid Simulator

❑ Assessment of a building with BRB

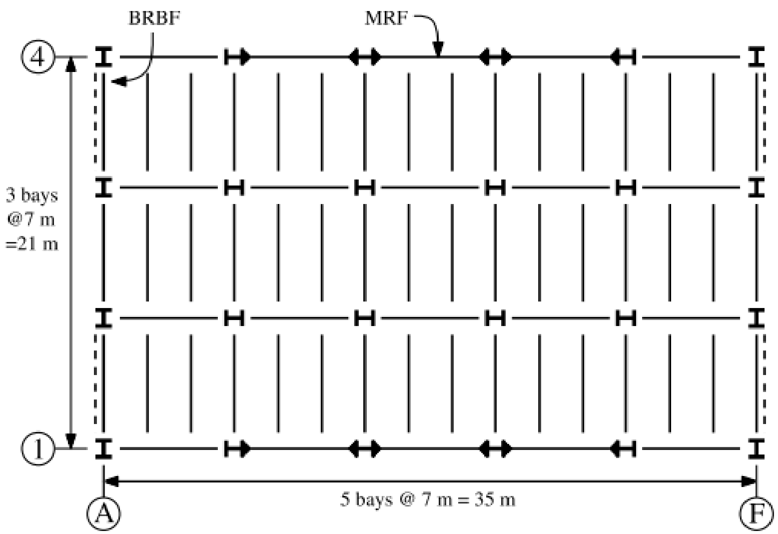
- Features
  - Robust nonlinear hysteretic response
  - Similar response to full-scale BRBs
  - Reusable after replacing the damaged parts
  - Adjustable stiffness and strength
  - Uniform axial stress/strain:
    Scaling only on length

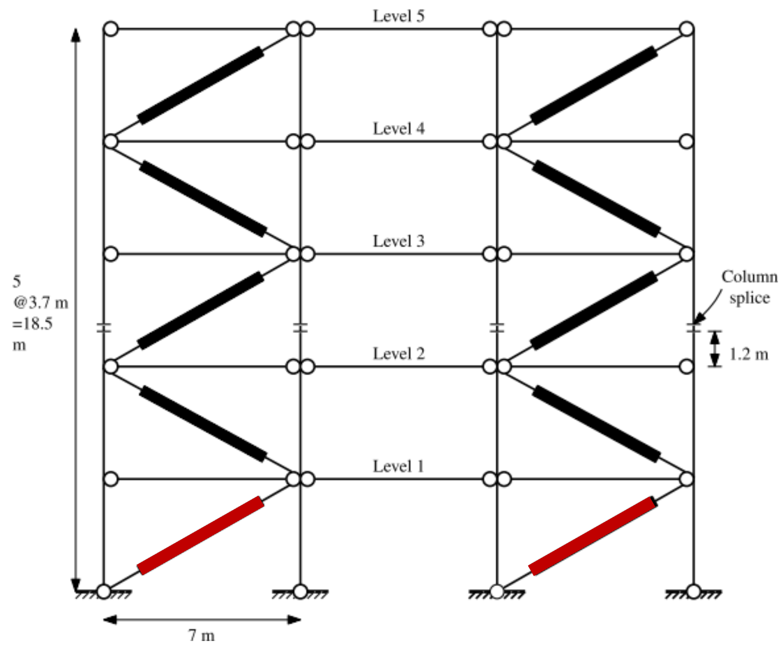
- Design
  - Threaded rod-pipe element:
    Threaded rod yielding in tension and compression inside confining pipe
  - Combinations of 2, 4, and 6 threaded rod-pipe elements
  - PT end connections
  - Threaded rod: Facilitated connection and replacement of core



UT10 Hybrid Simulator

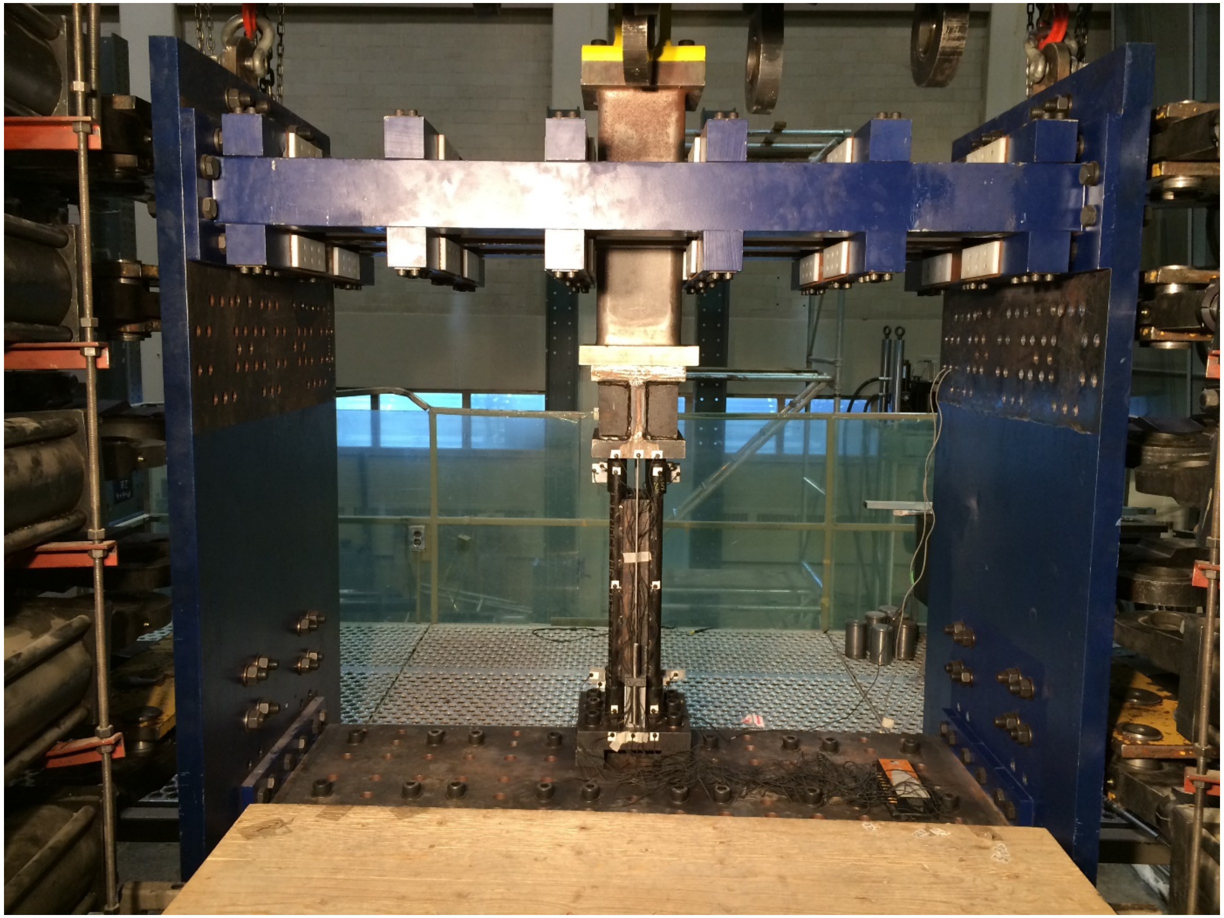
- **Assessment of a five-storey Steel Frame with BRBs**
  - Location: Los Angeles, Soil: C, Period: 1.2 sec
  - Design based on real-scale adjustable BRB specimen
  - First story BRB tested physically, the rest modeled in OpenSees
  - The rest of BRB models calibrated based on cyclic test results





UT10 Hybrid Simulator

- Assessment of a five-storey Steel Frame with BRBs



UT10 Hybrid Simulator

Assessment of a five-storey Steel Frame with BRBs

- Location: Los Angeles, Soil: C, Period: 1.2 sec
- Design based on real-scale adjustable BRB specimen
- First story BRB tested physically, the rest modeled in OpenSees
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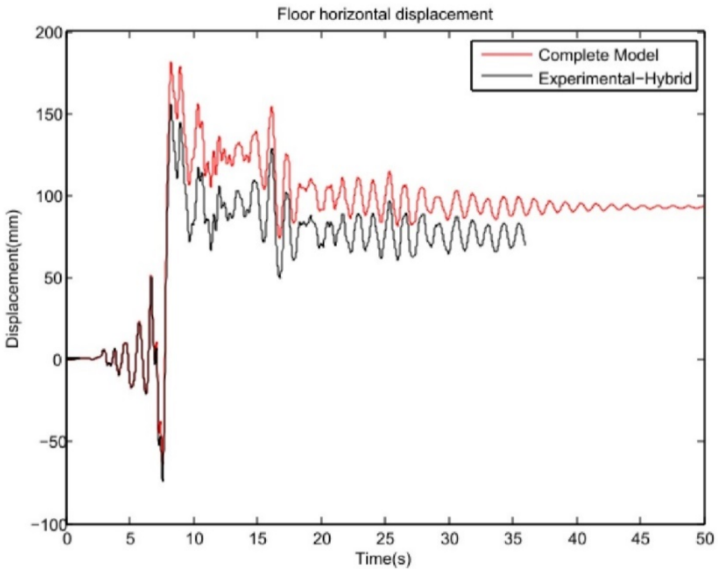
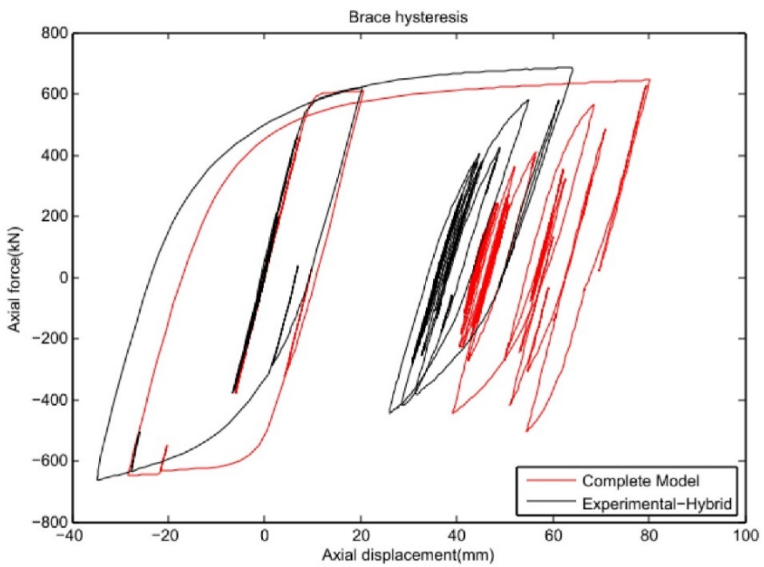
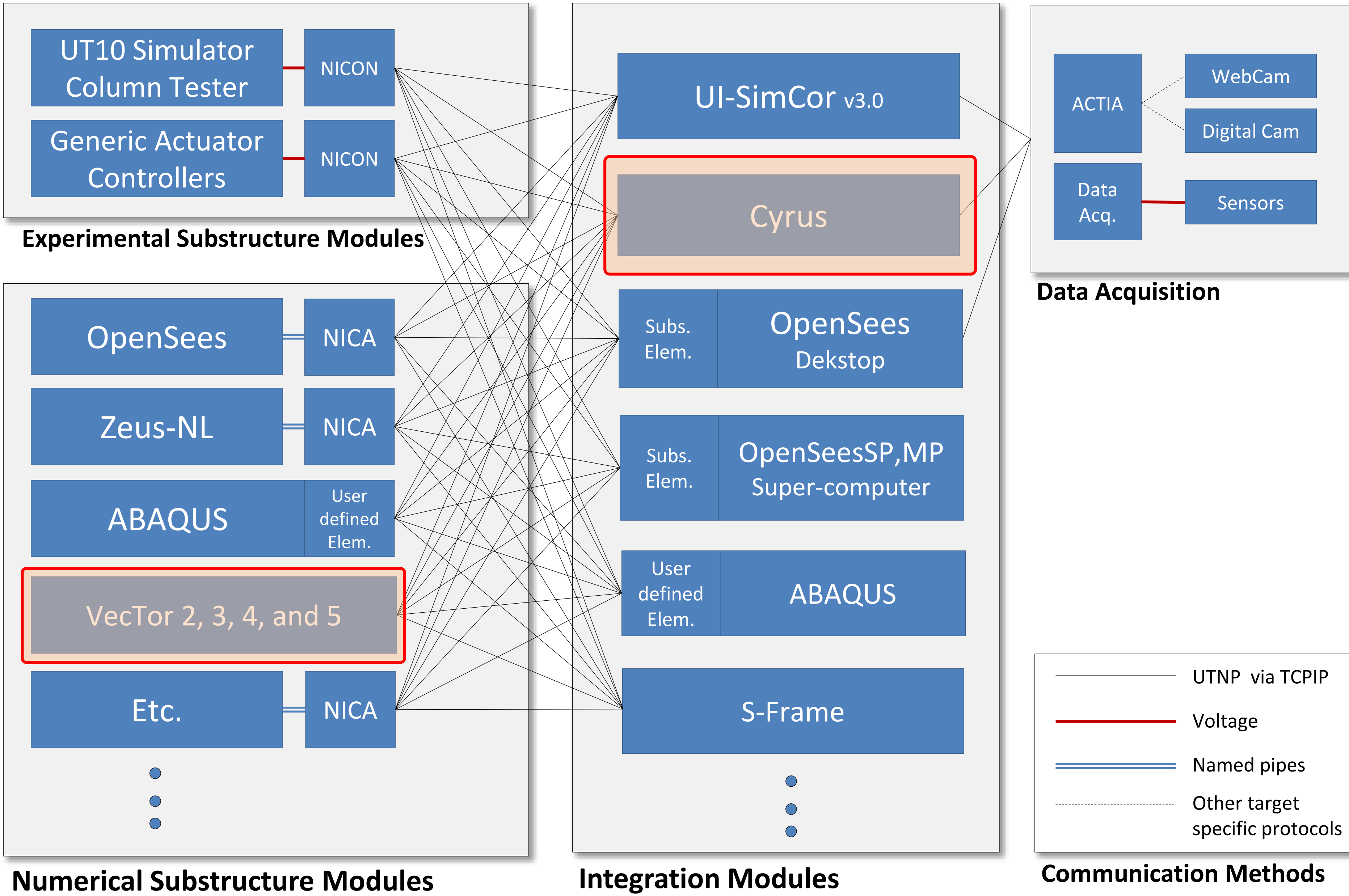
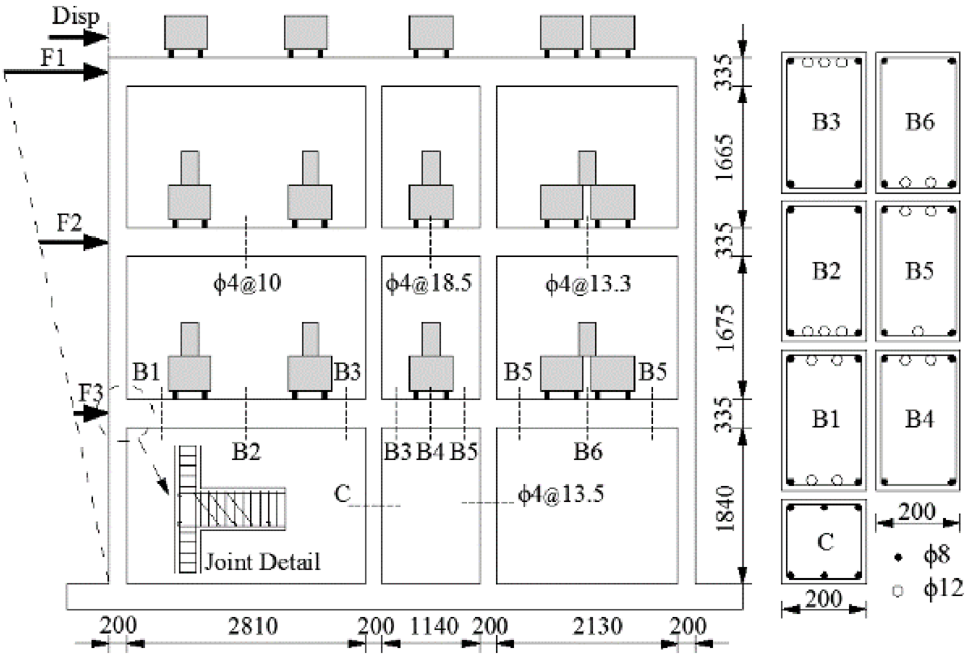




UT-SIM: Application Example 3



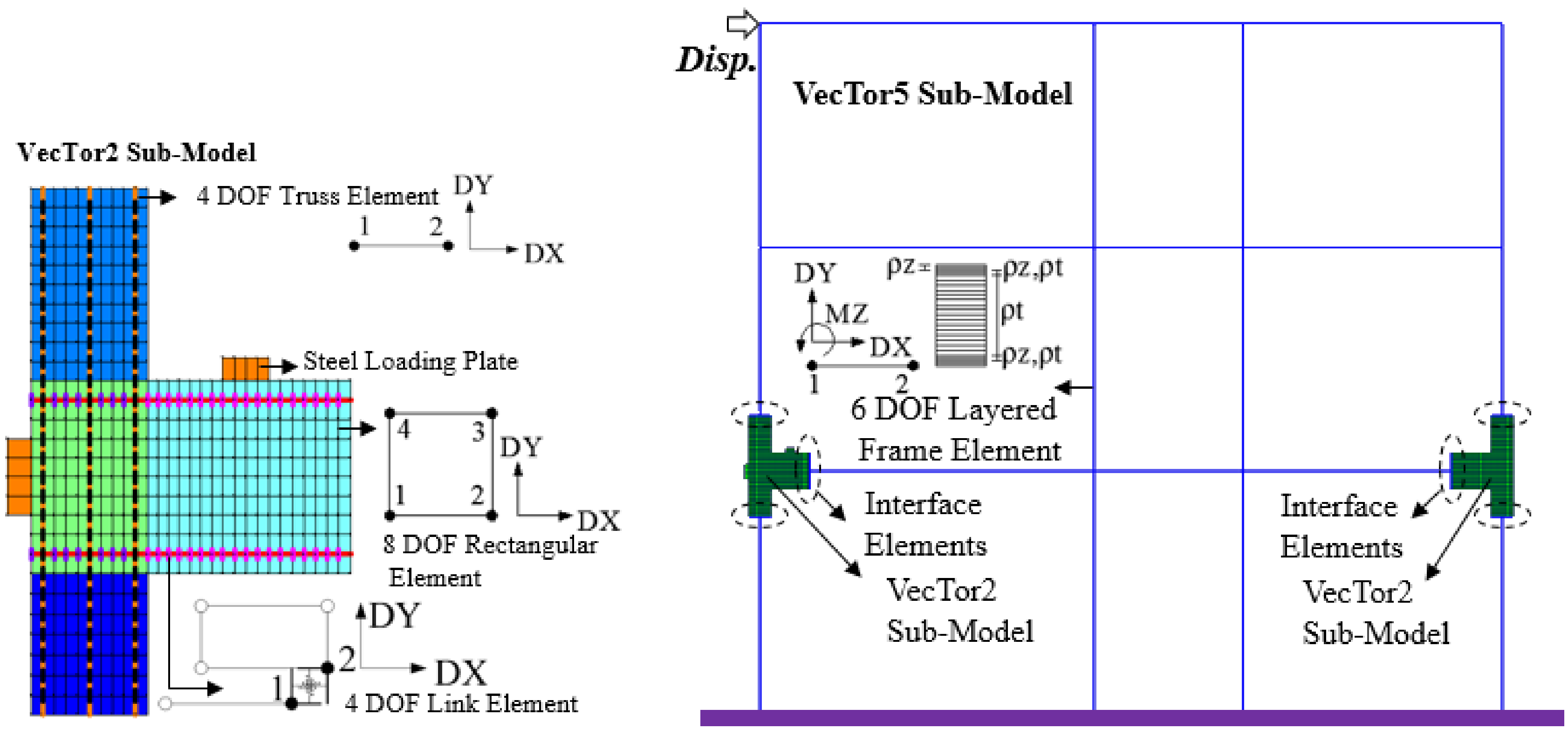
Three Story RC Frame



(Calvi et al. 2002)

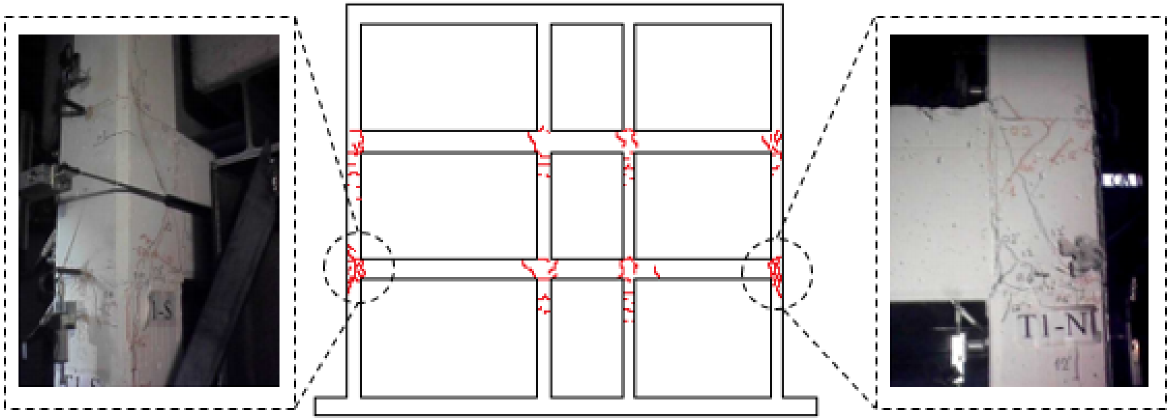
Sadeghian, V., Vecchio, F., and Kwon, O. (2015) "An Integrated Framework for Analysis of Mixed-Type Reinforced Concrete Structures," CompDyn, Crete, Greece, May 25-27.

Three Story RC Frame

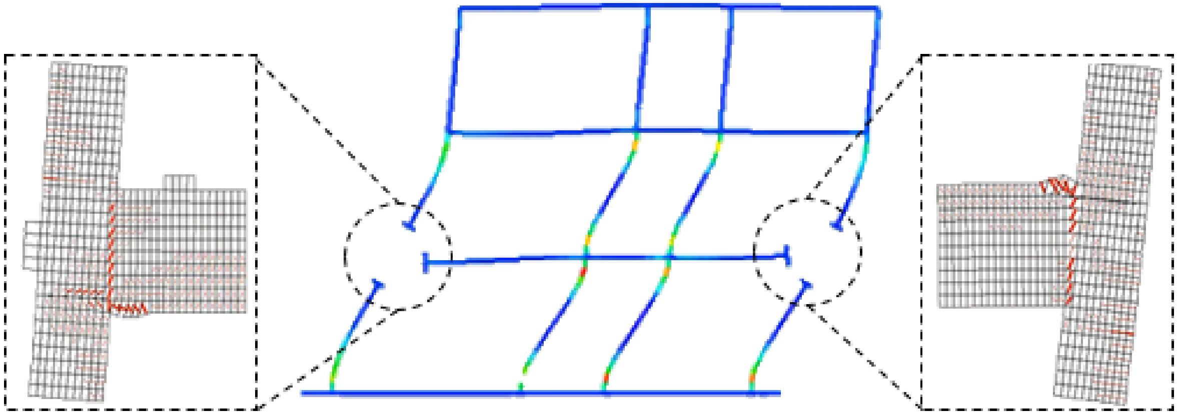


Mixed-Type model (VecTor2 and VecTor5)

Three Story RC Frame

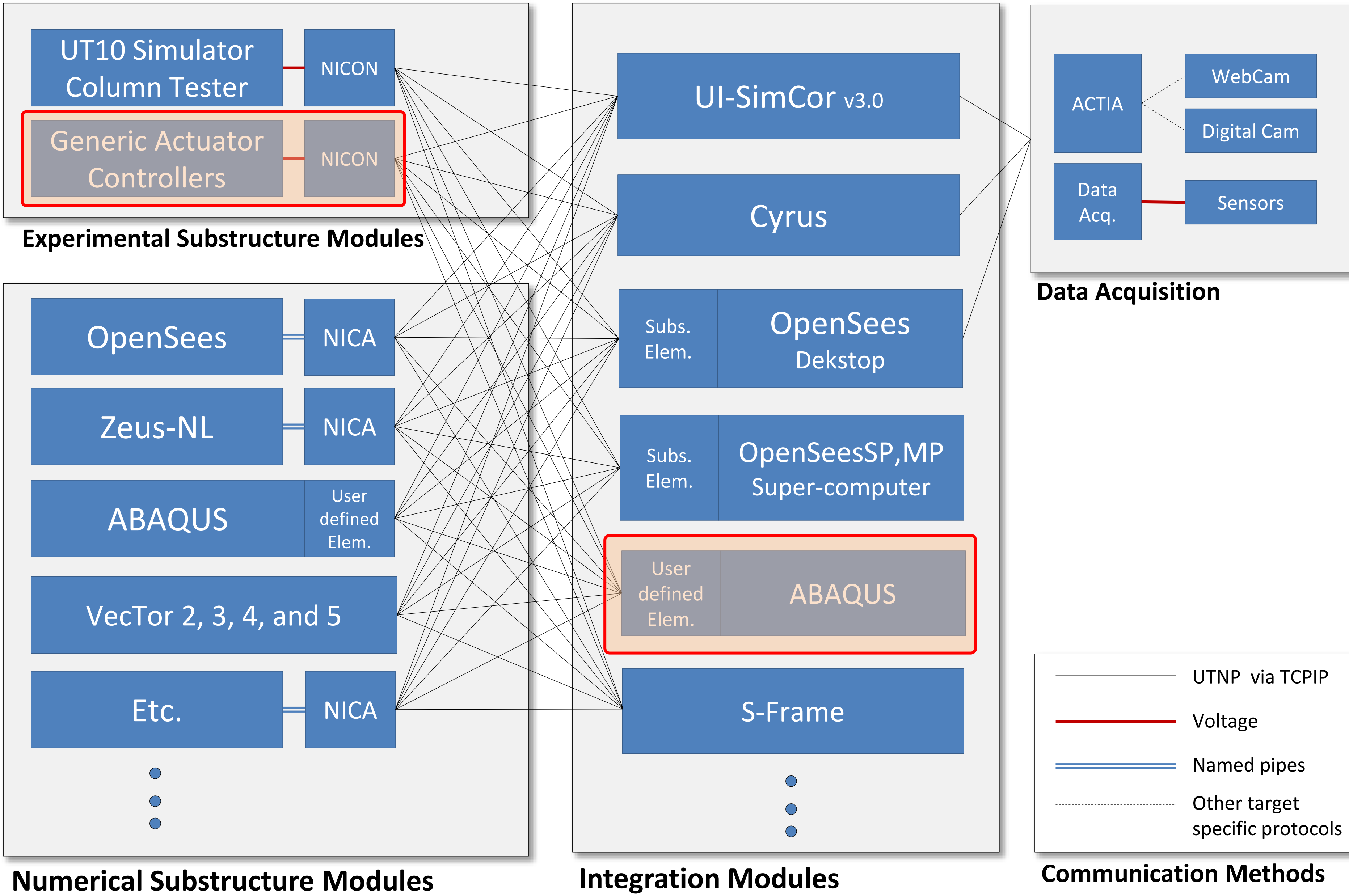


Experimental crack pattern



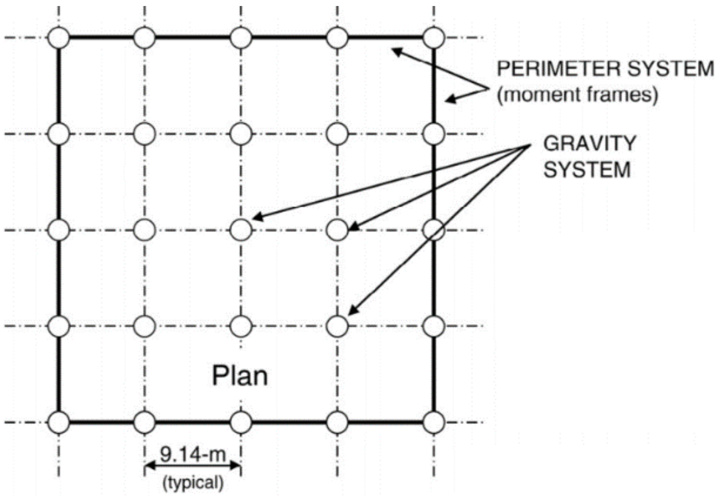
Mixed-Type crack pattern

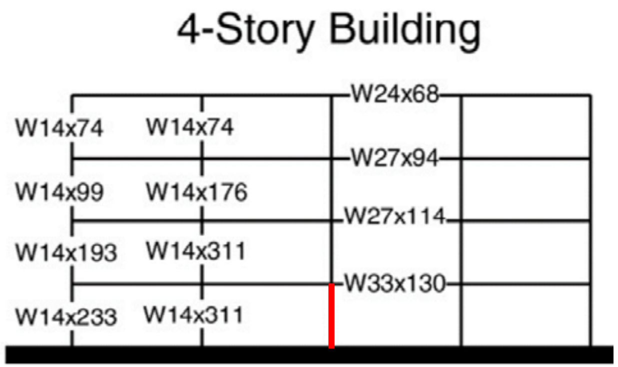
UT-SIM: Application Example 4



Hybrid Fire Simulation

- **Research in progress: Hybrid fire simulation**
  - System level performance assessment of a structure under various fire scenarios





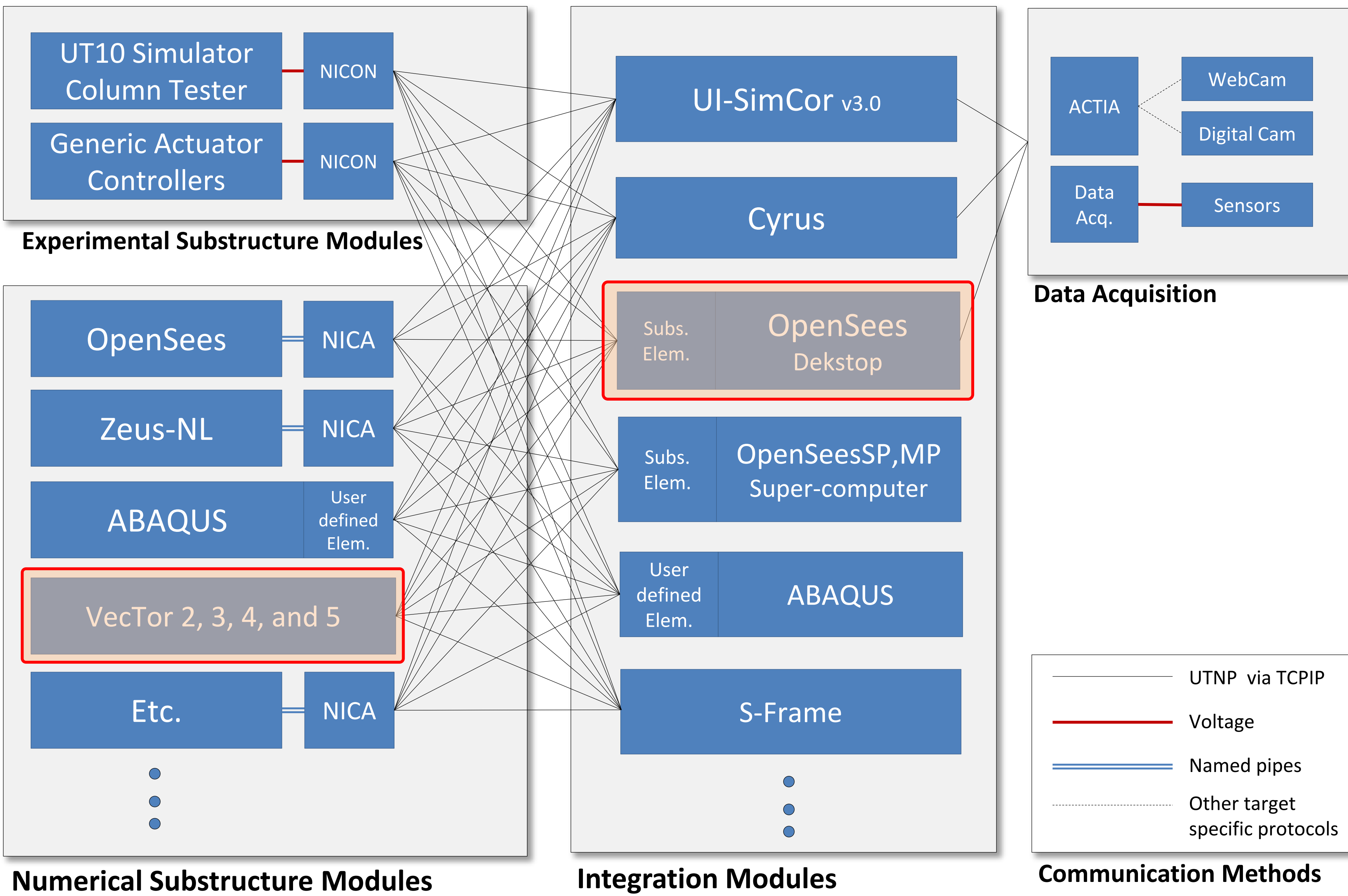
Jin, J., and El-Tawil, S. (2005). “Seismic performance of steel frames with reduced beam section connections.” J. Constr. Steel Res., 61(4), 453–471.

Hybrid Fire Simulation

- **Research in progress: Hybrid fire simulation**
  - Collaboration with Korean Institute of Construction Technology and Colorado State University
  - Scheduled to start testing in September 2016

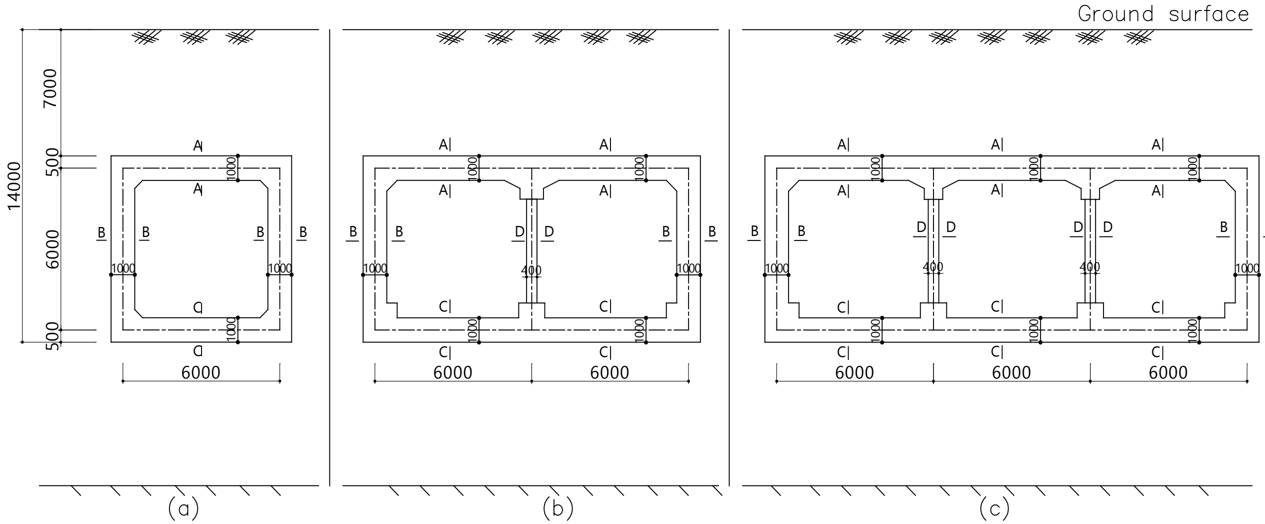
Fire testing facility in KICT (left) and CSU (right)

UT-SIM: Application Example 5



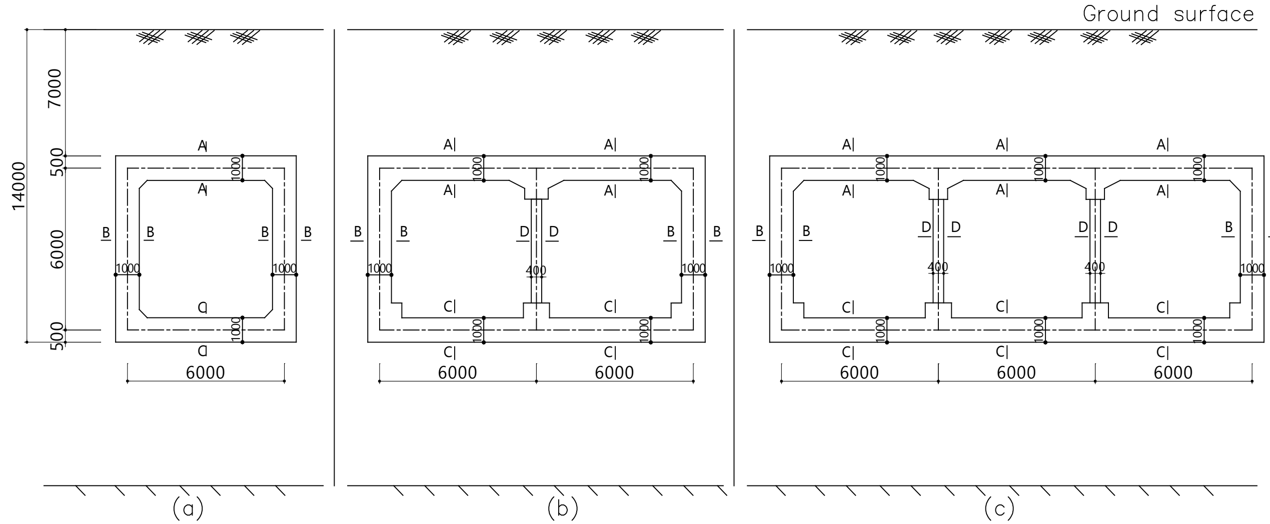
Soil-Underground Structure Interaction

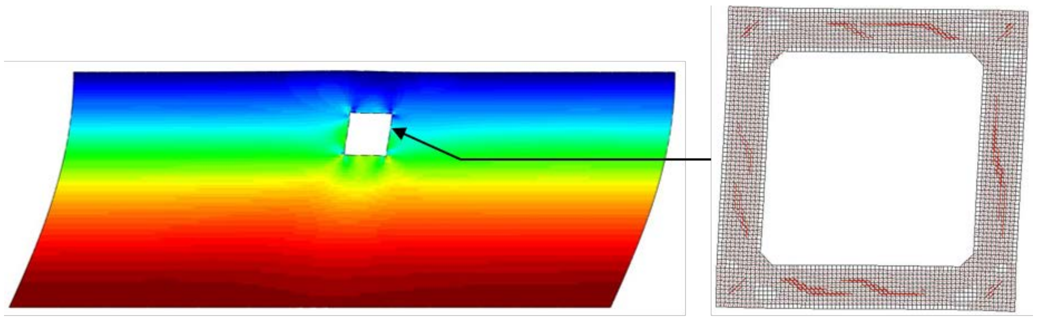
- Research in progress: Soil-Tunnel Interaction Analysis



Soil-Underground Structure Interaction

- Research in progress: Soil-Tunnel Interaction Analysis





OpenSees: Soil domain model VecTor2: Concrete tunnel model

Soil-Tunnel interaction simulation through UT-SIM framework

Work Package 2

- **Hybrid experimentation on principle failure modes of the soil-pipeline system**
  - Study of the soil-pipe stiffness by testing of a pipe segment at a reduced scale within a sand box to take into account the influence of soil compliance
  - Laboratory Investigation at the University of Patras on connection failure modes
  - Geographically Distributed Hybrid Testing for a pipe supported in five points between three partners: the University of Bristol, University of Patras, University of Toronto

Summary

- The implementation of hybrid simulation is generalized such that multi-platform substructure simulation can be readily carried out.
- Standard data exchange format and communication library has been developed and implemented.
- The network interface program, NICON, has been developed to facilitate the implementation of PsD hybrid simulation using a conventional actuator controller and low-cost AD/DA converters.
- The simulation method has been applied to various multi-platform hybrid simulations.
- As part of Exchange-Risk project, hybrid simulations are planned using the UT-SIM framework.

Thank you for your attention.